Single Manufacturing Platform Environment (SIMPLE) - Stage 2

Project Report

NI1032-REP-01

NUCLEAR AMRC
ADVANCED MANUFACTURING RESEARCH CENTRE

Project report

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Executive summary

The SIngle Manufacturing PLatform Environment (SIMPLE) project has completed the first phase of developing an autonomous welding system capable of detecting welding imperfections as they occur. This was completed over a two stage project running between May 2017 to August 2019. The vision for this autonomous welding system is that, in addition to realising significant productivity gains when welding thick section pressure vessels, the system's configuration would also prove the capability to successfully integrate several intelligent end effectors into multi-functioning manufacturing platform.

The realisation of this vision would enable significant cost savings by reduction of lost time to component movement, lower factory footprint requirements, improved consistency of component quality, reductions in non-conformance and reduced number of rejections and improved overall performance by realising the potential of 4th Industrial Revolution (4IR) technologies. The project consortium lead by the Nuclear AMRC has developed an in-process weld monitoring system that integrated a variety of sensors to capture and synchronise the data for analysis. The sensors selected for the project were:

- Acoustic sensors – developed by the Nuclear AMRC
- Vision sensor – developed by TWI
- Ultrasonic sensor – developed by University of Strathclyde Centre for Ultrasonic Engineering and Peak NDT
- Process monitoring sensors – developed by the University of Sheffield Physics and Astronomy department
- Laser sensors – developed by Nuclear AMRC
- Emerging sensors – developed by Nuclear AMRC

In addition, the system integration was performed by the AMRC Design and Prototyping Group with advanced supplementary work executed by the Nuclear AMRC to investigate the use of novel modelling methods to predict the weld geometry.

Each of the sensors were selected based on their ability to directly or indirectly detect welding imperfections or those process conditions that are known to lead to them. Work was conducted for each of the sensors to develop methods to correlate the data to welding imperfections in isolation. In addition, the integrated system was then made to capture and synchronise the data from the array of sensors during welding. The system was then demonstrated using a suite of experimental trials that represented a circumferential pressure vessel weld joint design used within the nuclear manufacturing industry.

Through the course of this project the technologies have been developed to an average TRL of 3. They are now at the point at which they are ready for exploitation in a subsequent collaborative R&D programme. In addition to this proposed work to continue the development of the autonomous welding system, additional research is required in other manufacturing processes if the vision of the single manufacturing platform environment is to be widely realised.

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A. Introduction

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1 Introduction

The 'SIngle Manufacturing PLatform Environment' (SIMPLE) project is a large collaborative research and development project funded by the Department of Business Energy and Industrial Strategy (BEIS). This report covers the work undertaken in stage 2 of the project, a 20 month technology development programme. The main outputs of the stage 1 feasibility study are summarised later in this chapter with Appendix 5 containing the full stage 1 report.

1.1 Nuclear innovation programme

As part of the BEIS Energy Innovation Programme BEIS expects to invest up to £180 million in nuclear innovation in the period 2016-2021. A key aspect of this investment is in the area of advanced manufacturing and materials. UK Government aims for the Advanced Manufacturing & Materials programme are (1):

- By 2021 to have established a strong manufacturing & materials R&D base to support the UK nuclear supply chain.
- By 2030 provide underpinning technology support to the UK manufacture of components for SMR and other reactor types.
- By 2050 facilitate UK industry developing a position as a significant global player in the deployment of SMRs and other advanced reactor technologies. Support BEIS in achieving its objectives:
- Ensuring the UK has a secure and resilient energy system
- Keeping energy bills as low as possible
- Securing ambitious international action on climate change while reducing carbon emissions cost-effectively at home

The work within the programme seeks to deliver the following benefits:

- Development and retention of key skills and capabilities required to design, manufacture, regulate and operate future reactors.
- Increased capability and competitiveness of the UK nuclear manufacturing supply chain.
- Nuclear technologies and components with enhanced safety and reduced costs.
- Reduced energy costs by implementing advanced manufacturing techniques.
- Improved nuclear sustainability by reducing waste.

1.1.1 History and Background

In 2011 the House of Lords Science and Technology Committee carried out an Inquiry into the UK's nuclear R&D capability and made a number of recommendations on where it viewed improvements were needed. In response the

Government published its Nuclear Industrial Strategy in March 2013. This described a clear and ambitious vision of a vibrant UK nuclear industry making a valuable economic contribution and providing the UK with a safe, reliable and affordable source of low carbon electricity. It also identified a series of initial actions to realise those objectives. These included the establishment of Nuclear Innovation and Research Advisory Board (NIRAB) and Nuclear Innovation and Research Office (NIRO).

NIRAB was initially established as a three year temporary advisory board in January 2014 and was charged with advising Government on the level, approach and coordination of nuclear innovation and R&D required to keep future energy options open and enable both domestic and international commercial opportunities to be realised. NIRAB initial term ended in December 2016 (2).

NIRAB was reconvened and reconstituted in 2018 and works in partnership with NIRO to advise Ministers, Government Departments and Agencies on issues related to nuclear research and innovation in the UK. (3)

NIRO is operated by the National Nuclear Laboratory (NNL) on an independent arms length basis and is primarily staffed by secondees from NNL and industry (2).

1.1.2 NIRAB report to government

In March 2016 NIRAB provided a report - UK Nuclear Innovation and Research Programme Recommendations – to the UK Government on the R&D needed to deliver its civil nuclear power objectives (4).

NIRAB developed recommendations for research, which were grouped into five key programmes. One of these areas was advanced materials and manufacturing.

On 7th November 2016 BEIS launched a competition for advanced materials and manufacturing (AM&M) under the Small Business Research Initiative (SBRI) which closed on 11th January 2017 (5).

1.1.3 Advanced Materials and Manufacturing

The AM&M phase 1 competition was split into 5 themes

1. Nuclear structural materials
2. Mechanisation and automation of component manufacture
3. Large scale component manufacture and assembly
4. Pre-fabricated module development and verification
5. Design codes and standards

shows the themes and proposed phases.

SBRI competitions are 100% funded and are open to all organisations that can demonstrate a route to market for their solution.

Furthermore the guidance document for the competition stated on page 7 (5);

'This competition covers the R&D required in the first two years of a 5 year programme. For all themes, applicants should consider forward planning and how each theme will develop at the end of the initial 2 years. However, this competition must have clearly defined outputs at the end of the 2 year period. '

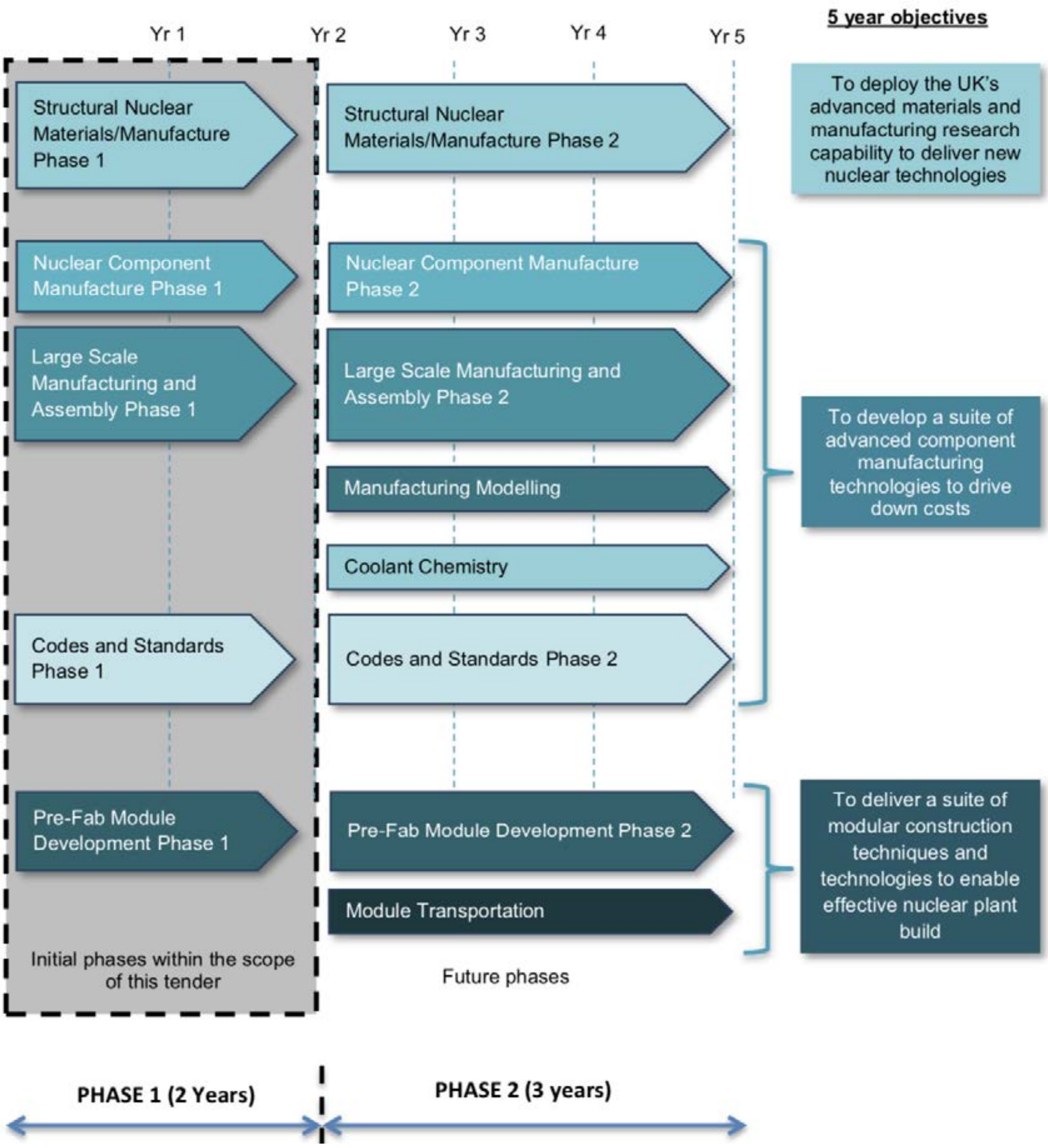

Figure 1-1: AM&M Themes and Phases (5)

While the competition was only for the first phase of 2 years, any submissions should be based around a 5-year programme. Due to the size of the budgets across the various themes, the competition consisted of 2 stages for Themes 1 to 3. Successful applicants were initially awarded Stage 1 contracts (3 months) to produce a feasibility study and if justified by the study, a stage 2 contract (20 months) would be awarded.

Based on the 5 year timescale, Nuclear AMRC submitted an appropriate bid into Theme 2 – the SIMPLE project – and was awarded a stage 1 contract in May 2017. The stage 1 report (see Appendix 5) was submitted in August 2017 upon which a 20 month contract for Stage 2 was offered starting in January 2018 for completion at the end of August 2019.

Nuclear AMRC's proposal into Theme 2 was that the 20 months of the stage 2 contract would deliver a proof-of-concept demonstrator to address the challenge of high cost and lead time in pressure vessel manufacture. This demonstrator would be the foundation for an integrated manufacturing platform deploying automated manufacturing processes to realise the desired cost reductions. The proof of the concept being that in 20 months we could successfully gather a wealth of synchronised data from multiple sensors monitoring a data rich, long lead time, prominent nuclear manufacturing process – mechanised gas-tungsten arc welding. This would provide the underpinnings for Phase 2 where the data could be used to improve the efficiency and robustness of the process with a potential to predict performance and mitigate costly errors. The 3 year Phase 2 would also miniaturise the sensors and build them into a 2/3rds scale demonstrator ready for commercialisation. The work would also look at other manufacturing processes that could leverage the developments of this work and realise the concept of disparate manufacturing processes co-existing in a collaborate environment.

1.2 The challenge

The SIMPLE project falls under Theme 2 of the AM&M area (Figure 1-1), with a focus on nuclear component manufacture. The challenge set for Theme 2 involved the automation of component manufacture to achieve the economies required to make reactors – particularly small modular reactors (SMR) – economically viable and attractive. This is to be achieved through a reduction in lead times and an increase of throughput with no detriment to quality or safety.

Activities within the theme could include technology transfer and development across automated joining, forming and casting as well as innovative machining, manufacturing and inspection technologies.

The specific outcomes of this theme were to include (5):

- An assessment and demonstration of advanced and automated manufacturing techniques and their repeatability for high value nuclear components.
- Improved cost effectiveness of inspection during the manufacture of large components used in nuclear reactors.
- Demonstrating compliance with existing codes and standards or a plan for the development of appropriate new codes and standards.
- A forward programme intended to better define the requirements of the remainder of the 5 year funding period. This should include an outline plan to deploy and commercialise the outputs.

The Nuclear AMRC proposed that the SIMPLE project was to also;

- Demonstrate the feasibility of deploying multiple and varied manufacturing processes on a single platform to achieve increased efficiency.

- Address the challenge of serial production in a factory environment and how a data driven manufacturing approach can add value to industry.

1.3 Single platform manufacturing environment

The ethos behind SIMPLE is that of a system made by integrating conventional and advanced techniques in cutting, welding, inspection, and additive manufacture to be able to co-exist in a single location utilising shared axes with the ability to perform in-process inspections. The SIMPLE concept also aims to identify how data and the use of data and data sharing between processes can enhance manufacturing and address the challenges that exploit the opportunities of adopting the 4th Industrial Revolution (4IR) technologies. The current state of the arc welding technologies lack process security and this is in part due to the difficulty in monitoring process input and output variables. For the demonstration of the SIMPLE concept, an arc welding process, namely the gas-tungsten arc or TIG-141 process was specifically selected due to its provision of a data rich environment and therefore a process that could significantly benefit from the deployment of 4IR technologies. The ultimate aim will be to enable and justify the potential use of closed-loop welding processes, which are not currently used in the nuclear industry, will result in a higher confidence level of weld integrity with increased process security. The purpose of the SIMPLE concept is for it to become a common platform for the manufacture of nuclear-scale components, which will reduce the cost, time, and space associated with sequential welding, machining, and inspection activities thereby reducing the inherent risks of moving large components. These activities, combined with those benefits offered within those other research themes are aimed at reducing the overall cost of manufacture of pressure vessels by 50%.

Single platform manufacturing has great potential in the manufacturing of large components for the nuclear industry as well as offering significant benefit to other high-value manufacturing sectors such as energy, oil and gas, marine and aerospace. Large machining platforms are often limited in their manufacturing capability by having only a single spindle. This spindle is limited to material cutting tasks with the capability to exchange the cutting tool with a measurement probe for verification tasks. Many downstream operations, such as deburring, polishing, visual inspection, surface finish inspection and Non-Destructive Evaluation (NDE) are often required. With large machine tools there is the luxury of space within the environment to introduce other automated and mechanised technologies. This provides an opportunity to introduce autonomous systems to perform necessary non-cutting tasks in parallel, improving the productivity of the manufacturing platform and reducing the overall manufacturing time. Replacing the current system of traditional manufacture with a single platform will reduce the factory footprint, improve the consistency of component quality, reduce the number of rejections, improve the overall performance and improve the current UK competitiveness of large-scale engineering projects. The ultimate objective is to generate UK-owned IP that can be exploited worldwide across a wide range of applications and markets within various industrial sectors. The new technologies developed in SIMPLE will lead to new workforce skills and provide significant contributions to address the UK nuclear skills gap.

1.4 Large component manufacture

In the nuclear industry, components can be extremely large and heavy, which complicates and lengthens the manufacturing process due to the extra challenges of movement and subsequent setting up of the component. This is particularly true for the manufacture of high integrity nuclear components such as pressure vessels, which even for SMRs, measure several metres in diameter and of thick-wall section. Currently, the arc welding of pressure vessels is carried out using mechanised processes requiring a demanding level of human interaction, usually highly skilled welding operators to observe the welding operation. The size of the components found in the nuclear industry necessitates that this be undertaken remotely via cameras integrated into the end effector. The high temperatures, high intensity arc light and restricted view given by the welding geometry, present a limitation to the quality of any images that can be captured with the available hardware. The operator must indirectly observe the welding process and, based on this limited information, make manual interventions where necessary via adjustment of the welding parameters (e.g. wire feed rate) or the position of the welding electrode and arc to ensure the component meets the requirements of the manufacturing code(s) and structural integrity standards. Not only is this time consuming, it presents many risks to both safety and component integrity. The low confidence in this process leads to numerous mid-process NDE – again a manual, highly skilled activity, dramatically increasing the time required to complete a thick section pressure vessel weld primarily due to the cooling and heating cycles involved.

1.5 Commercial benefit

A market analysis was performed in the stage 1 feasibility study and is included in Appendix 5 of this report. A summary of the findings of that analysis is as follows;

- Significant new nuclear build programmes will be required both domestically and globally to meet the future demand for secure reliable low-carbon power sources.
- The global market for mid-range pressure vessels is expected to be in the range of £360m-£675m annually.
- To achieve the Government's vision, the cost competitive manufacture of high value nuclear components needs to be addressed.
- Cost reductions would be achieved by the introduction and development of process monitoring and verification technologies employed in other sectors.
- It is estimated that 25-30% of manufacturing cost can be attributed to material handling, which would be significantly reduced by use of a single manufacturing platform.
- Cost saving measures employed in automated pressure vessel manufacture can be applied across the wider manufacturing supply chain ranging from high-integrity fabrications to decommissioning waste containers.

2 Project scope

Stage 1 of the project was a feasibility study into the applicability and impact of SIMPLE to nuclear component manufacture. This was to study the concept in detail and define the required scope for stage 2 of the project. The activities across stage 1 included market research, gap analysis, technology down-selection and functional specification.

The focus of stage 2 of the project was to begin developing the SIMPLE concept by addressing the difficulties in real-time monitoring and control of weld input variables, and the poorly understood relationship between process inputs and outputs. Narrow groove gas tungsten arc welding (NG-GTAW) was selected because it presents a manufacturing process with a wide range of variable inputs, opportunities to capture and analyse data sources in-process as well as being a process that is difficult to co-exist alongside other manufacturing processes. The project was to be delivered through a series of parallel developmental work packages including weld modelling, sensor technology development, software and hardware development, and signal processing.

A full-scale, integrated, mechanised arc-welding demonstrator was to be built at the Nuclear AMRC and equipped with multiple sensors that were capable of inspecting and monitoring nuclear components welded in real-time. The demonstrator in this project selected mechanised GTAW and inspection technologies, as this is one of the most widespread joining technologies used in pressure vessel manufacture. The Nuclear AMRC's longer-term vision for SIMPLE is to integrate other operations such as laser welding, machining, inspection, and additive manufacturing to achieve cost reductions in components across the entire primary loop and balance of plant.

Another opportunity for reducing capital investment costs in facilities is the potential development of a new welding head, which has potential to be a portable technology that can be utilised outside of the single manufacturing platform environment. This would be deployed using technologies developed in the Nuclear AMRC led Theme 3 NIP AM&M sister project 'Intelligent Fixture for Optimised and Radical Manufacturing' (InFORM). This will allow manufacturing to be taken to the component, or potentially outside of the factory. As well as reducing costs, it will offer environmental benefits by reducing the transportation of large components over significant distances.

The SIMPLE approach is to use multiple sensors to capture the complete range of flaws that are capable of being generated during or just after the weld has solidified. This data can then be used to build a body of evidence to verify the quality of the welds and build confidence in the process. The overall aim is to use this evidence to justify the elimination of costly and potentially risk ridden intermediate non-destructive evaluation (NDE) that is used routinely in the fabrication of thick-section pressure vessels.

The proposed system, which can use real-time monitoring and a feedback loop to the welding process operator, will aim to be capable of avoiding the known issues of thermally induced risks such as delayed hydrogen cracking, handling damage, radiological protection issues, joint misalignment, re-establishment of preheat and the sheer elapsed time that NDE invokes. Another unique aspect of SIMPLE is that the output from all of the sensors employed will be fed to a single interface that is capable of analysing the data flow and determining if the weld process is within acceptable parameters and potential identify if flaws are being generated. Where possible, corroboration between two or more sensor systems will be sought before halting the welding process and the resulting soft sensor (2 or more combined data channels, may provide a deeper insight than a single data channel alone).

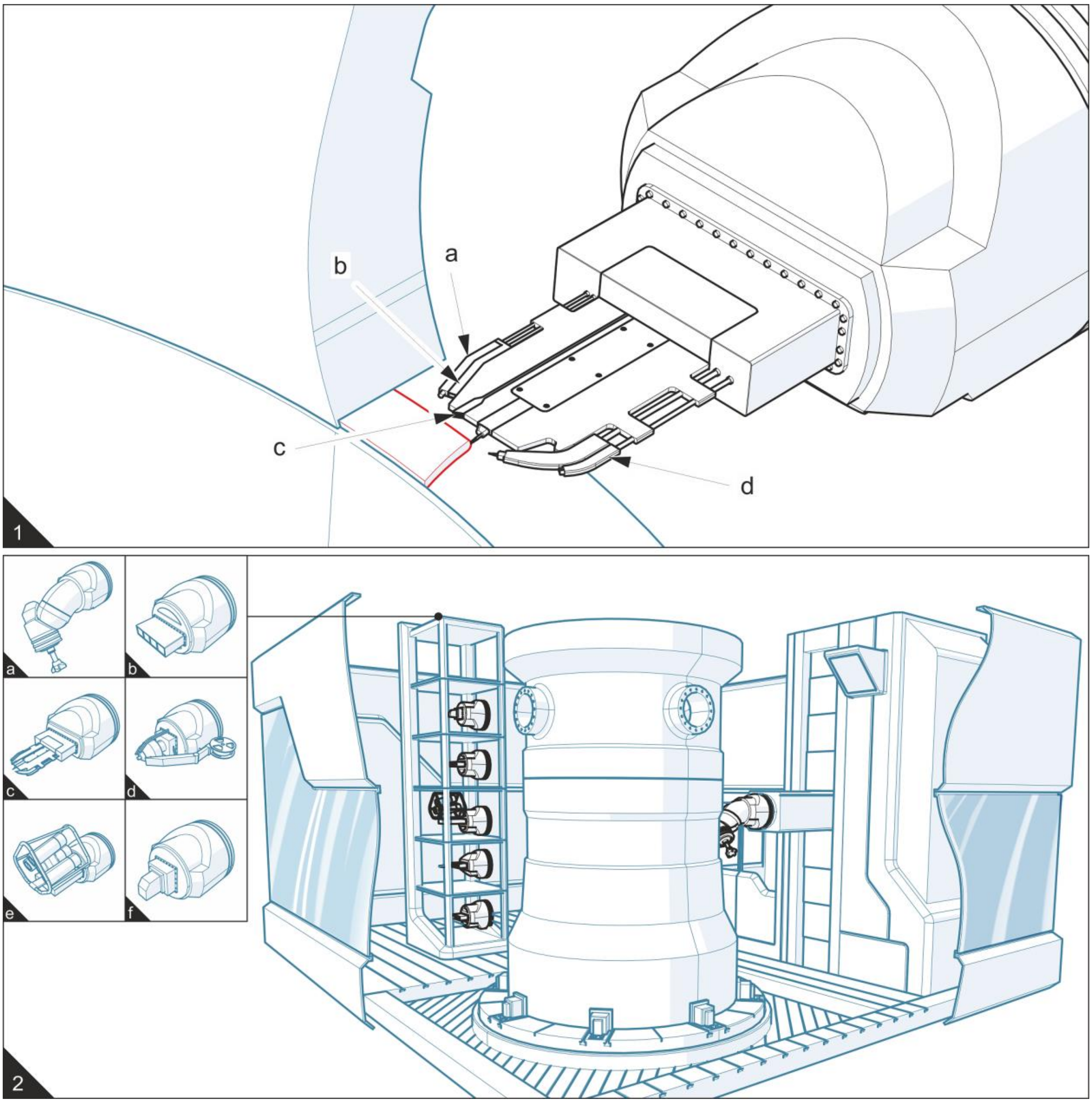

Figure 2-1: SIMPLE concept art.

1 (top): welding effector with integrated sensors a) acoustic b) laser c) vision d) ultrasonic

2 (bottom): Manufacturing platform with multiple effectors a) multi-axis milling b) ultrasonic inspection c) welding d) laser diode cladding e) non-contact 3D scanning f) vertical turning

The following sensor technologies were specified to be developed:

- Laser vision sensors for both geometry and process monitoring aspects.
- Acoustic signal sensors for detecting audible features that correlate to welding imperfection.
- CCD/CMOS based vision systems to complement laser vision systems in terms of cost reduction.
- Measurement of current and power variation during the welding process.
- Ultrasonic based sensor transducers for internal weld imperfection analysis.
- Emerging sensors capable of inferring new information from the as-welded material such as stress and strain.

In addition to the individual sensor development, the following research was also to be performed:

- Investigations into novel modelling methodologies to predict the weld geometry from input welding parameters.
- Definition of a data standard capable of integrating all potential data sources into one synchronised data file capable of being correlated to the exact location on the welded material.
- A system demonstrator integrating the sensors capable of continuous data sampling (laser, acoustic, vision and power monitoring) into the data file for near to real-time processing.
    - The close to real-time processing of this single data file was deemed out of scope and to be conducted in the follow-on programme.
- Dissemination of the research conducted in the project.

2.1 Future commercialisation

The project delivered an integrated sensor system capable of capturing synchronised in-process sensor data to monitor the mechanised GTAW process. Additionally, the technical development required to correlate the individual sensor data to welding imperfections, or the conditions that led to them was conducted. The work required to then deploy and commercialise this system, as well to develop the other enabling single platform manufacturing technologies, will need to be the subject of future research, as originally planned for the subsequent 3 year programme. The details of this future programme are outlined in section 5 of this report.

3 Project Structure

3.1 Project consortium

The lead contractor is the Nuclear Advanced Manufacturing Research Centre (Nuclear AMRC), part of the University of Sheffield (UoS), who are sub-contracting work packages to Peak NDT (an SME), TWI, the University of Strathclyde (UoStr), as well as the Advanced Manufacturing Research Centre (AMRC) with Boeing and the UoS Applied Particle Physics and Engineering Department. SIMPLE includes SMEs, research and technology organisations, Catapult Centres and universities who bring complementing skills and approaches to the project.

3.1.1 Nuclear AMRC

The Nuclear AMRC brings together the experience and resources of industry leaders from across the civil nuclear manufacturing supply chain with the expertise and innovation of leading universities. Its mission is to help UK companies win work in the global nuclear marketplace. It has established itself as the centre of excellence for UK nuclear manufacturing and has strong working relationships with all the named project subcontractors and supporting partners (named in the stage 1 report in Appendix 5). The Nuclear AMRC has substantial experience in managing large collaborative projects and has valuable expertise in project management, nuclear research and development (where stringent regulations need to be followed and large, high-value components are typical), NDE, machining, and the development of new and optimised welding processes for the most demanding nuclear applications. Nuclear AMRC supported the development of the acoustic sensor, laser sensor and emerging sensor technology and the SIMPLE demonstrator was located at their Rotherham facility.

3.1.2 University of Sheffield Department of Physics and Astronomy – Enabling Sciences for Intelligent Manufacturing group (ESIM)

The Applied Particle Physics and Engineering Department conducts world-leading research in advanced engineering, particle detector technologies, irradiation studies, tracking detector development and robotics for radioactive environments. Previous projects relevant to this proposal include the Science and Technology Facilities Council Innovations Partnership Scheme Advanced Aerospace Alloy Joining. This department's expertise supported the in-process signal monitoring tasks in sensor development.

3.1.3 AMRC Design and Prototyping Group (DPG)

The AMRC DPG is situated at the centre of active research themes across the AMRC and the wider University of Sheffield, enabling them to combine world-class research and development with innovative and flexible design capabilities. They utilise in-house high-precision machining processes, additive manufacturing, fabrication, advanced analytical tools and clean room facilities to develop next generation prototypes. Their current portfolio includes: the design and build of a high performance, large volume additive manufacturing machine; the development of an unmanned ground support vehicle; the successful launch of powered and free-flight unmanned aerial vehicles; the re-design of a pyro-electric fuel shut off valve and the development of next generation orthopaedic devices. DPG's expertise supported the systems integration.

3.1.4 Peak NDT

Peak NDT is a technology provider specialising in the development, manufacture and support of multichannel and phased array ultrasound controllers for use in the NDE industries. They provide consultancy services, including feasibility studies, technique development and ultrasonic inspection modelling. They have expertise in ultrasonic technology and experience in integrating and commercialising inspection techniques in other sectors. Peak NDT are involved in non-destructive test and sensing technologies and add to the expertise and equipment necessary to develop in-process ultrasonic sensing in sensor development. Peak NDT's expertise supported the development of the ultrasonic sensor work package which was led by UoStr. As a UK SME, it is intended that Peak NDT will play a major role in system implementation and exploitation in future phases of the SIMPLE project.

3.1.5 University of Strathclyde Centre for Ultrasonic Engineering (CUE)

The Centre for Ultrasonic Engineering (CUE) has over 30 years of expertise in the design and implementation of ultrasonic transducers and transducer systems across a broad range of industrial sectors. CUE addresses markets in non-destructive testing, industrial process ultrasound, condition monitoring, automation, underwater sonar and biomedical applications with expertise in ultrasonic transducer manufacture, system prototyping, instrumentation hardware, system simulation, robotics, metrology, data processing software and image analysis. UoStr led the development of the ultrasonic sensor in close collaboration with Peak NDT.

3.1.6 TWI

TWI are a UK research and technology organisation with expertise in materials joining and industrial engineering processes. They specialise in innovation, knowledge transfer and solving problems across many aspects of manufacturing, fabrication and whole-life integrity management. TWI brought expertise in visual sensors gained from the 'CAMWELD' project, previously funded by Innovate UK, to support and provide leverage to the SIMPLE project.

3.2 Work package structure

The project structure and the location of the development carried out in each work package is outlined in Table 3-1.

Table 3-1: SIMPLE project structure

WP no.	Work package name	Lead organisation	Location in this report
1	Stage 1 feasibility report	Nuclear AMRC	Appendix 5
1.1	Market research		
1.2	Gap analysis		
1.3	Technology down-selection		
1.4	Functional specification		
1.5	Project management		
2			
2.1	Weld modelling	Nuclear AMRC	Chapter B
2.2	Sensor development		
2.2.1	Data standard and system architecture	AMRC DPG	
2.2.2	Acoustic sensor	Nuclear AMRC	Chapter C
2.2.3	Ultrasonic sensor	UoStr CUE	Chapter D
2.2.4	Visual sensor	TWI ltd	Chapter E
2.2.5	In-process signal monitoring	UoS ESIM	Chapter F
2.2.6	Laser sensor	Nuclear AMRC	Chapter G
2.2.7	Emerging technology sensor	Nuclear AMRC	Chapter H
2.3	Systems integration	AMRC DPG	Chapter I
2.4	Demonstrator	Nuclear AMRC	Chapter J
2.5	Dissemination	Nuclear AMRC	Chapter K
2.6	Project management	Nuclear AMRC	

4 Summary of project outputs

Full details of the developments carried out in each work package is outlined in chapters B through to I. The challenge and initial TRL/MRL of each technology at the start of the project is outlined in accordance to the methodology outlined in Appendix 2. Each report details the work undertaken, recommendations for future work and a route to commercialisation. In addition, the result of an independent TRL/MRL assessment of each technology at the conclusion of the project is stated. Appendix 1 provides a complete justification for TRL/MRL assessments of all work packages.

4.1 Overall impact of the project

Figure 4-1 and show a summary of the TRL assessment for every work package as validated by the Principal Investigator (PI).

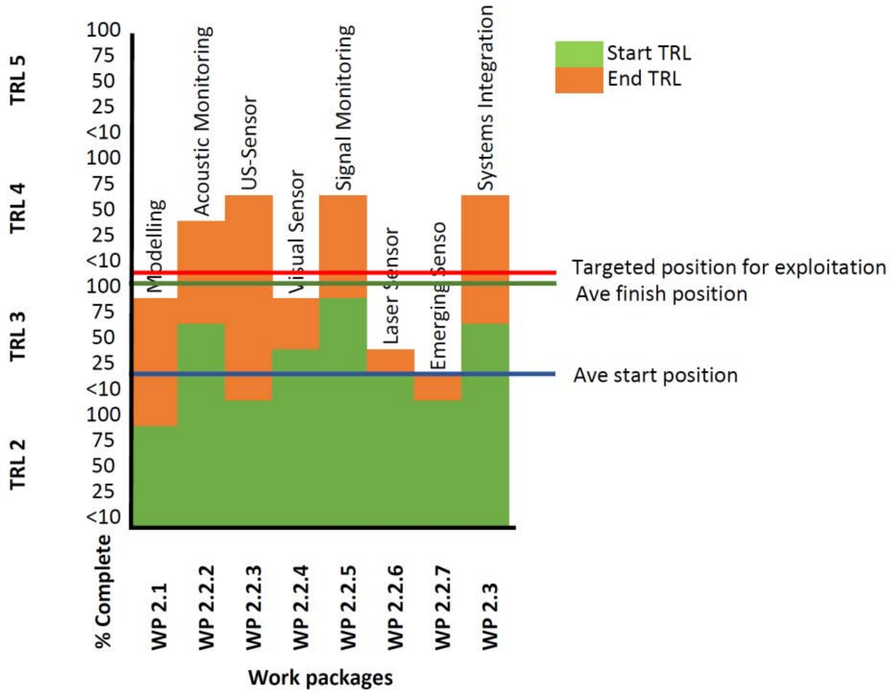

Figure 4-1 Start and finish TRL

As can be seen, the majority of work packages achieved significant progress up the TRL and MRL scale. The acoustic, ultrasonic, signal monitoring sensors alongside the integrated system have all reached a technological readiness of which they are ready to start being exploited in conjunction with the supply chain and should be prioritised for further development in future projects.

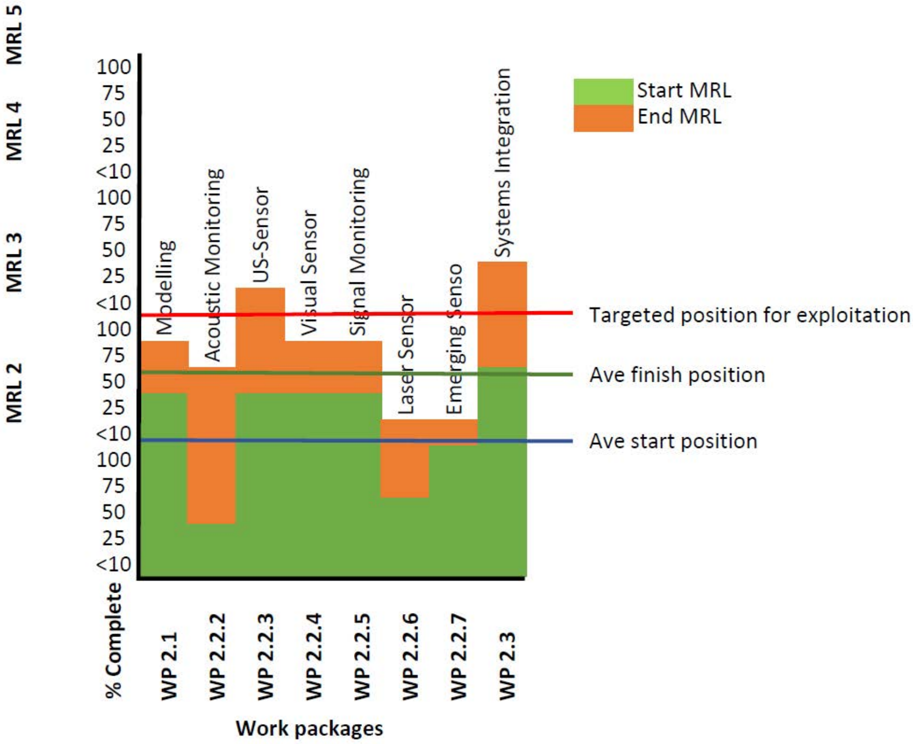

Figure 4-2: Start and finish MRL

4.2 Weld modelling

This programme of work assessed the use of adopting Artificial Neural Networks (ANNs) to predict weld bead geometries using the "Bead-On-Plate" (BOP) melt run methodology, with a view to determining a confidence in its qualitative transferability applied to novel weld joint designs, e.g. narrow-groove butt weld joints.

The current limitation encountered within such applications involves the accuracy of the prediction (acceptable error function). This can be improved through the use of large datasets, suitably weighted coefficients and fine-tuning the hyper parameters of the ANN, e.g. number of neurons, number of layers and the learning rate.

The BOP and narrow groove weld joint configurations are treated as individual parts of the project. In this work package, the BOP melt run method was the main focus of attention due to the limited base material stocks and processing time available to produce the quantity of data needed for an accurate cross transfer assessment. To confidently adopt the inputs from the BOP form to directly predict the outputs for a multiple-pass "weld joint" configuration, an example being a single sided U-groove butt weld, was not possible due to the limited experimental data associated with such an arrangement. To develop this technology further, and increase the accuracy of the system, large quantities of data will be required to study, develop and validate the algorithms for multi-pass operations.

4.3 Sensor development

4.3.1 Acoustic sensor

This work package developed an approach to use airborne arc sound to predict the presence of welding defects. Prior research has generally been laboratory-based and has found that acoustic data from the welding application is rich in information that can be correlated to the process (such as welding penetration) or the presence of welding imperfections. There is however a challenge in scaling up this technology out of the laboratory and into industry due to the numerous sources of noise in an industrial environment.

This work developed techniques for the removal of the background noise found in a working environment while also developing advanced signal processing techniques to correlate features in the acoustic data to the presence of known imperfections. A real time algorithm was developed with the capacity of predicting whether a weld was within the confidence levels of the baseline acceptable conditions, or whether there was a high likelihood of the presence of an imperfection. The outputs of this algorithm are shown in Figure 4-3. With further development, and with input of data from the other sensors, the SIMPLE system should have the capability to then classify which imperfection is present.

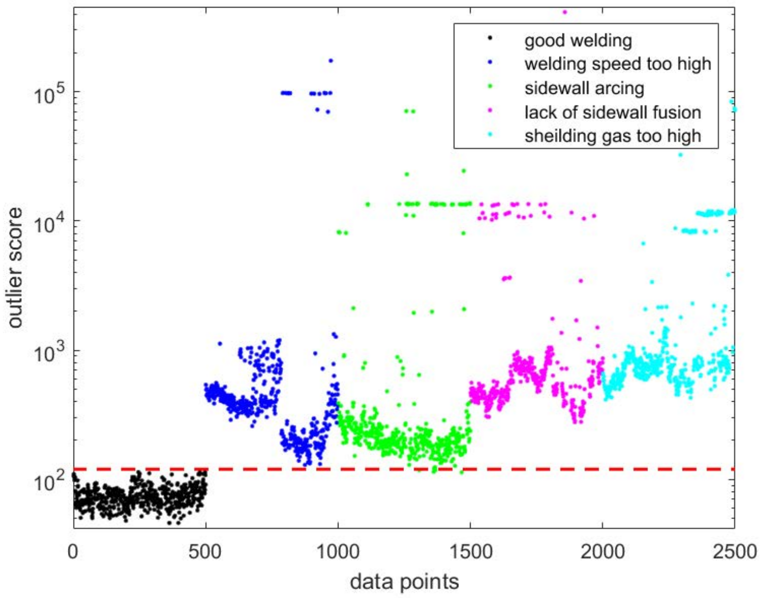

Figure 4-3: Results from frequency domain analysis of acoustic data

4.3.2 Ultrasonic sensor

Ultrasound inspection is a well-recognised technique, with international standards adopted for inspecting completed welds, albeit at ambient temperature. This work package developed a methodology of performing state-of-the-art phased array ultrasonic inspections during the welding process. In-process inspection of multi-pass welds has to address a number challenges, including high temperature damage to the sensor, correcting for beam bending associated with temperature gradients in the material and identifying a mechanism to avoid false reporting of Lack of Fusion (LOF) defects from unfinished parts of the weld.

There is significant research currently being applied to high temperature array assemblies suitable for weld inspection but these are all still at low TRLs and were not expected to have been developed to a suitable TRL within the SIMPLE project timescales. As a result, the emphasis was on adopting current commercial state-of-the-art devices into approaches that can address the above challenges. The benefit of in-process ultrasonic inspection is to provide early defect detection, saving costs by:

- Providing early process control feedback, that in turn provides continuous decision points for accepting or indicating timely and efficient re-work positions to minimise downtime, energy costs and consumable waste.
- Avoiding movement of the workpiece to a separate inspection facility, and then returning it for re-work
- Automating the inspection process, which also improves consistency of detection

This work demonstrated the feasibility of the technology at UoStr by performing ultrasonic scans of a conventional V weld preparation immediately after welding using a robotic manipulator (Figure 4-4) at representative welding temperatures.

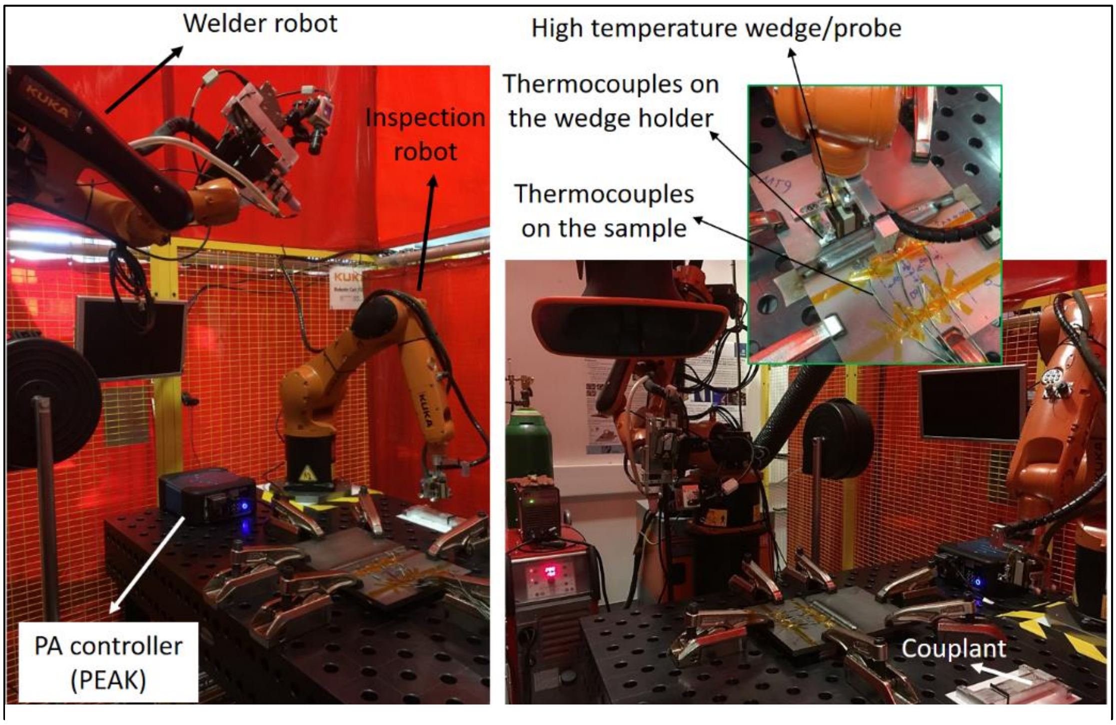

Figure 4-4: Ultrasonic inspection welding cell at Univeristy of Strathclyde

4.3.3 Visual sensor

This work package developed a visual weld monitoring system for in-process monitoring. This used a high dynamic range (HDR) camera in conjunction with an ANN analysis system capable of processing the camera data locally and in real-time. The use of HDR technology allows greater information to be inferred from the captured images and the automation of the monitoring process removes factors such as operator fatigue from the welding process.

For this application, the network receives an input in the form of a series of images (video “frames”), similar to how the human brain processes motion. Each image is then analysed via an image recognition algorithm to segregate it into a set of pre-determined categories. These are based on the conditions that an operator would potentially observe, such as optimal welding, lack of fusion, burn-through or similar. If a specific number of non-optimal categorised frames are detected, the welding process can then be interrupted.

Welding trials were conducted to generate training data for the ANN, with images being correlated to imperfections observed in destructive post-weld testing of the coupons.

The system showed potential to be able to classify the camera images to the selected set of welding flaws under study, however the accuracy of the system was not shown to be consistent or high enough for industrial adoption at this stage. Further work is required to provide further training data to the ANN, as well as to develop alternative means to improve the confidence of the system.

4.3.4 In-process signal monitoring

This work package scaled up a high frequency in-process signal monitoring system previously developed by ESIM from a low current laboratory system to a high current system capable of being applied to thick section GTAW applications found in nuclear component manufacture. The in-process signal monitoring of DC-pulsed GTAW processes can reveal the presence of faults in the welding process, signified by instability in the welding-arc voltage.

The upgraded system was fully integrated into the SIMPLE demonstrator with the data captured and proof-of-concept data correlated to welding imperfections. While the data is promising, considerable effort is now required to establish a statistically valid baseline for any given welding schedule in terms of an arc-stability profile. Understanding how to classify welding-process defects based on this profile will require a considerable amount of new data to enable the ongoing development of new classification algorithms.

4.3.5 Laser sensor

This work package developed a laser sensor scanning system to monitor weld preparation geometry, make sure that weld is clear of debris and record the topology of each weld pass as it is laid down. This data can then be used to detect any abnormalities of the surface that could subsequently develop into weld defects. Challenges specific to this welding application, notably the use of deep, reflective, narrow groove cavities with near-vertical walls were attempted to be overcome with the use of multiple scanners integrated into the system. However the reflection issues could not be overcome and so the demonstrator deployed a single laser, perpendicular to the weld which could scan the weld cap but not the sidewalls. This 2D profile was captured alongside the other sensor data during welding and showed capability to determine the bead profile of each welding pass, as well as potential to detect foreign debris in the groove.

4.3.6 Electronic speckle pattern interferometry

This work package developed a novel application of an emerging sensor technology for use in the chosen welding application. The market analysis undertaken in Stage 1 of the SIMPLE project recognised that there is a clear need for a measurement instrument, capable of providing a portable, high resolution, fast, three dimensional weld measurement system adept in simultaneously providing residual stress data. Residual stress data is essential for validating component integrity, and the development of such a system would have significant impact across the nuclear lifecycle. Speckle-based metrology, specifically, electronic speckle pattern interferometry (ESPI) was selected as the technology to be developed.

An ESPI test rig with the potential for portable measurement was specified, designed and built in the laboratory by the Nuclear AMRC. Proof of concept measurements were taken showing the capability of the system to detect sub-micron deformations in a test sample with proposed future work being required to correlate these deformations to residual stress values before the development of a system, which could operate within a shop floor environment.

4.4 System integration

A demonstrator system capable of integrating the sensor technologies from the other work packages was developed at the Nuclear AMRC. Furthermore, this was to be designed as an open platform to allow additional sensors to be added to the system, as required for future research. The data was to be stored in a single synchronised data structure, with the data correlated back to the physical location of the weld under study. After a full requirements capture the system was specified and then manufactured by the AMRC DPG. The system was successfully tested at the Nuclear AMRC as part of the demonstrator welding trials with the laser, acoustic, vision and power monitoring sensors capturing data simultaneously. In addition to the open system architecture, the system also has significant processing power, allowing computationally intensive analysis of the data to be performed locally.

4.5 Welding system demonstrator

To demonstrate the proof of concept of the system, the fully integrated welding monitoring system was used to capture and store the synchronised in-process data captured during a representative weld. The welding application was chosen to include the use of production scale welding equipment to perform a simulated thick section butt joint of nuclear grade pressure vessel steel. The suite of welding trials gathered baseline data on welds deemed to be acceptable to international standards. In addition, an array of welding conditions were selected to generate flaws in known locations of the weld coupon. This data was used to prove the concept of real-time data capture, and can form the basis of the development of the multi-sensor data processing algorithms in future research.

5 Deployment and follow-on research

The output of the SIMPLE phase 1 project is an integrated system consisting of numerous technologies at a maturity of TRL and MRL of 3 to 4 (Figure 4-1 and). This system is now ready to be applied to industrial applications and developed towards a field deployable prototype, however significant research is still required to develop the analysis methods to accurately and consistently detect the welding imperfections to an acceptable confidence level. In addition to the welding flaw detection system, additional enabling technologies are needed to bring the single manufacturing platform concept to fruition.

The deplotment path identified in this section has been developed via engagement with nuclear technology vendors, manufactures, and other key stakeholders industrial research community. This has been achieved through dissemination via the Nuclear AMRC membership, direct engagement, technical assessment and peer review of the project as well as general engagement with the supply chain. A description of the dissemination activities completed during the project is given in Chapter K.

5.1 Route to market

The 2-year SIMPLE Phase 1 project was scoped with a focus on SMR pressure vessel manufacture as a precursor to a 3-year demonstrator programme showing a potential route to market. As the landscape of the nuclear sector has changed since the time SIMPLE Phase 1 was scoped, there is a large degree of uncertainty in developing a pressure vessel manufacturing system in the UK optimised for the SMR and/or AMR market. To realise near term benefits to the UK supply chain and to reduce the risk associated with the development it is necessary to find complimentary applications in which the underpinning technologies can be developed and taken to market. When the uncertainty around the roll out of the next phase of the UK civil nuclear power sector (be this SMR, AMR or fusion) is reduced, the now mature underpinning technologies can then be combined and realise the true potential of a single manufacturing platform environment.

5.1.1 In-process welding flaw detection

The immediate need for pressure vessel manufacture for SMRs is receding however there is still a strong business case for developing this technology in other areas of nuclear (and non-nuclear) manufacturing. The major productivity benefit of a system that can automatically detect welding imperfections in real time is in applications where a flaw would not be detected until later in the manufacturing process and at which point there is significant cost required to rectify that imperfection. This cost can be in the form of the following;

- Manufacturing time to perform significant rework to remediate an imperfection buried under numerous deposited layers.
- Significant lost time moving the component between the inspection and manufacturing areas (for example crane utilisation can often be a bottleneck in large production facilities).

- Lost time in manipulating, setting up and pre-heating large components ready for welding.
- Downstream productivity losses on the production facility schedule by tying up high value equipment.
- Documentation costs associated with any repair work.
- Through life costs associated with detection, monitoring and structural integrity assessments of manufacturing flaws and repair work in service.

High integrity pressure vessels were selected as the use-case for this project as all of the above consequential costs are incurred from the presence of welding imperfections, however use-cases where even one or two of the above consequential losses are found would also yield a benefit. During the dissemination of the SIMPLE project at various conferences in the UK and overseas there was significant interest from industry for:

- Nuclear new-build and decommissioning applications (e.g. pipework for Hinkley Point C, waste containers etc.).
- Welding applications that are difficult to inspect but have lower quality assurance requirements
- High volume welding of low value items (e.g. balance of plant pipework, structural rebar/supports etc.)

5.1.2 Single manufacturing platform enabling technologies

The route to market for fully integrated single manufacturing platforms for nuclear manufacturing is less clear as there is a lack of immediate demand for large scale multifunction manufacturing centres of this kind. However there have been recent developments in small scale additive-subtractive machines which have found application in gear and drivetrain manufacture, die-tool repair and cladding applications (6). While these machines offer an opportunity to prove the concepts of single platform manufacturing significant, further developments will be required in the areas of cross-process/collaborative control systems, process validation, part inspection and large component manufacture. In addition these machines incorporate conventional soluble oil coolant which is not feasible on the large open machines that are utilised in nuclear component manufacture during machining and also necessitates cleaning between subtractive and additive processes.

Prior to a commitment from government/industry and selection of a reactor technology to deploy at scale within the domestic UK market, it is difficult to define the specific development path for single manufacturing platforms that will be capable of satisfying the sudden increase in demand for large high integrity components. As with the in-process weld monitoring, is it therefore necessary to find near term applications for the technologies required to enable fully integrated SIMPLE machines to be deployed. These enabling technologies are;

- Advanced coolant technologies for deployment in open additive-subtractive manufacturing cells
- Manipulator and control system development for multi-process applications
- Integration and automation of inspection technologies
- Cross process data integration.

Upon successful development of these technologies, large scale single manufacturing platforms will be ready to meet the expected need from the next generation of UK civil nuclear power plants.

5.2 NIP AM&M Phase 2

The next phase of the AM&M programme was launched on January 16th 2019 and closed on 15th March 2019.

Some of the key features of the AM&M Phase 2 competition were:

- Proposals must be based around a Phase 1 technology
- The competition was to be grant funded, with an expectation of industry to contribute 40-50% of the total project costs
- The projects would finish at the end of March 2021 and should have a route to commercialisation based on this deadline

The Nuclear AMRC submitted a proposal to lead a development programme that would have addressed the major barriers to deploying single manufacturing platform environments in industry. The programme was structured across numerous strands, each focussed on the enabling technologies identified in section 5.1.

5.2.1 Automated NDT/NDE

This strand sought to develop advanced and automated NDT and NDE technologies such as robotic computer tomography systems, use of ultrasonic time-of-flight systems as an alternative to radiograph inspection, and high temperature ultrasound methods for applications in hazardous and harsh environments. The ambition of this work stream was to automate the final inspection process and then use this data to aid new and advanced structural integrity assessment methodologies. The ultimate aim would be to leverage the data gathered during the in-process inspection to reduce the burden on final inspections.

5.2.2 Machining

A single manufacturing platform that incorporates arc welding and machining will need to ensure that the machining process does not frustrate the execution of welding operations. Historically the issue with traditional machining processes is that soluble oil coolant is used to improve the efficiency of the cutting process but this contaminates the surface for any subsequent welding processes. Machining using super-critical CO_2 ($scCO_2$) not only overcomes the contamination issue but, as demonstrated in the InFORM project, can make significant reductions in machining time. $scCO_2$ machining was identified as an enabling technology in Phase 1 of the single platform project proposal capable of performing welding and high productivity machining in one manufacturing cell.

The Phase 2 strand of the SIMPLE programme seeks to develop technologies that will enable the wider uptake of this sustainable manufacturing technology within the supply chain. Current applications of $scCO_2$ coolant systems are limited to small-to-medium size numerically controlled machine tools as the coolant must be routed through the spindle which involves major modification to the internals of the machine tool. This strand seeks to develop and demonstrate a side-feed tool holder applicable to a variety of machine tools, including the large machining centres required for nuclear component manufacture.

Another potential package of work within this strand could be the modelling of advanced machining strategies. Modelling of tool paths would allow for the development of algorithms to ensure consistent feed-rates within machine tools, optimising the machining process and increasing productivity and environmental sustainability.

5.2.3 On-machine inspection

In this strand, an array of on-machine inspection technologies for use with large reactor parts and structures was to be developed and integrated onto the manufacturing system. Choreographing these technologies that link on-machine inspection tools and traceable methods such as interferometry systems, advanced error mapping checks and temperature compensations for large machines, will be fundamental in the development of smart and advanced infrastructures that reduce takt-times and facility footprints.

5.2.4 Control systems integration

To develop the capability and interoperability of multi-function manufacturing centres, this strand seeks to demonstrate robotic machining and welding within one manufacturing cell. This will build upon the work from Nuclear AMRC's H2020 COROMA programme and will develop the necessary control systems and data architectures needed to switch between different manufacturing processes. Near-term use-cases for such systems could be the automated repair of weld defects, utilising outputs from the in-process weld detection, or that of automated repair of damaged tooling. The real-time data generated in these processes would be further processed and refined to allow factory simulation to evaluate and respond to bottlenecks through the monitoring and processing of real-time manufacturing process data.

5.3 Future Work

The proof of concept of the analysis methods implemented on the discrete sensor outputs and the integration of the discrete data streams into a combined data flow has been demonstrated as the main output of the SIMPLE project. To realise the commercial benefit of the in-process welding imperfection detection system, a follow-on programme of work is required to make the system suitable for application in a commercial facility. If this system is also then to become an integral technology within a single manufacturing platform environment, complimentary programmes that follow the scope set in the NIP AM&M phase 2 SIMPLE phase 2 proposal are required to realise the full potential of such a system.

A route to implementation of a fully autonomous welding imperfection detection system is stated in Chapter J. This proposes a development path in which the autonomy of the system is slowly increased across three phases. The first phase would display the output of the real-time analysis to the welding operator and then halt the process on detection of an imperfection. The second phase would develop the autonomous control strategies based on process data captured from the system implemented in the first phase with the final phase implementing these methods in a fully autonomous system.

The following is an outline of a potential R&D programme that would aim to develop the technology towards MRL 6 and see the completion of the first phase of the development path.

- Technology development of a field deployable prototype (1-2 years)
  - Selection of a current application in the UK supply chain
  - Baselining the system to new materials, geometries and welding processes
  - Refinement of the analysis methods and optimisation of the sensing technologies for this application
  - Development of continuous high temperature ultrasonic phased array inspection and integration into the data capture system
- Development and commercialisation of the imperfection detection system (1-2 years)
  - Further refinement of the analysis methods
  - Robustness testing and process verification
  - Control systems integration
- Parallel activities
  - Underpinning research to implement machine learning into welding control systems to predict and correct welding imperfections in real time
  - Technology transfer into the welding production systems sector
  - Review and alignment of development to manufacturing and inspection codes and standards, with interventions into the revision of the codes where necessary

5.4 Summary

At the time of publication it is believed that any subsequent AM&M competitions in the near term will be based on the key features of Phase 2 and will require completion by the end of the 2016-2021 budget period. As such, any phase 3 projects will need to be delivered in 12-14 months, assuming that they launch in Q1 2020. For such a short period it is expected that any follow-on work from the SIMPLE project will continue to develop the fundamental technology but will not be able to deliver a commercially deployable system. If the funding invested in this research (and the research performed in the other strands of the AM&M phase 1) is to not be wasted, then there will need to be an additional mechanism found to fund the follow-on development.

Each of the subsequent chapters provides detailed recommendations to enable the specific technology in discussion to be exploited. In totality these recommendations provide a clear development plan for the SIMPLE programme and comprise a range of maturity levels with research durations ranging between 1 and 3 years.

It is therefore proposed that the recommendations from this report form a basis for a follow-on to the Nuclear Innovation Programme beyond 2021 .

References

1. BEIS. *Nuclear Innovation Programme - Call for advanced manufacturing and materials phase 2: guidance notes.* s.l. : BEIS, 2019.

2. NIRAB | About Us. *NIRAB.* [Online] [Cited: 4 September 2019.] http://www.nirab.org.uk/about-us/.

3. NIRAB. NIRAB | About Us | About NIRAB. *NIRAB.* [Online] [Cited: 4 September 2019.] http://www.nirab.org.uk/about-us/about-nirab/.

4. —. UK Nuclear Innovation and Research Programme Recommendations. *NIRAB.* [Online] [Cited: 4 September 2019.] http://www.nirab.org.uk/media/6233/uk-nuclear-innovation-and-research-programme-recommendations.pdf.

5. BEIS. *Guidance for Applications - Anvdanced Manufacturing and Materials Competition.* s.l. : BEIS, 2016.

6. *Latest Developments in Industrial Hybrid Machine Tools that Combine Additive and Subtractive Operations.* Cortina, Magdalena, et al. Materials, 2018, Vol. 11.

7. BEIS. Funding for nuclear innovation . *www.gov.uk.* [Online] 14 Jan 2019. [Cited: 9 Jul 2019.] https://www.gov.uk/guidance/funding-for-nuclear-innovation.

8. Polysoude. *The art of welding: narrow gap TIG welding handbook.* s.l. : Polysoude,Nantes,France, 2013.

9. *A study on the effect of weld groove designs on residual stresses in SS 304N thick multipass pipe welds.* A. Giri, M. M. Mahapatra, K. Sharma, P. K. Singh. 1, 2017, International Journal of Steel Structures , Vol. 17, pp. 65-75.

10. *ADVANCED WELDING TECHNOLOGY DEVELOPMENT FOR NUCLEAR REACTOR REPAIR Wei Tang, Jian Chen, Brian Gibson, Roger Miller, Scarlett Clark, Mark Vance, Zhili Feng, Keith Leonard.* Tang, Wei, et al. 2018, pp. 67-75.

11. *Welding Defects and Implications on Welded Assemblies.* F.YusofM.F.Jamaluddin. 2014, Comprehensive Materials Processing, Vol. 6, pp. 125-134.

12. *Quality control and assurance in fabrication of welded structures subjected to fatigue loading.* Stenberg, T and Barsoum, Z. s.l. : Welding in the World, 2017, pp. 1003-1015. 10.1007/s40194-017-0490-5.

13. *The detection of burn-through weld defects using noncontact ultrasonics.* Abbasi, Zeynab, et al. 1, 2018, Materials, Vol. 11. 10.3390/ma11010128.

B. Weld Modelling

Single Manufacturing Platform Environment (SIMPLE) – Stage 2

Weld Process Modelling

NI1032-REP-02

NUCLEAR AMRC
ADVANCED MANUFACTURING RESEARCH CENTRE

Project report

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Executive summary

Work package 2.1 – Weld Process Modelling

The objective of this programme of work was to assess the use of adopting Artificial Neural Networks (ANNs) to predict weld bead geometries using the "Bead-On-Plate" (BOP) melt run methodology, with a view to determining a confidence in its qualitative transferability applied to novel weld joint designs, e.g. narrow-groove butt weld joints. Initial conditions within the programme utilised the following software tools:

- Python programming language with Visual Basic Application base
- SciKit-Learn/MLPRegressor machine learning packages
- Multi-Layer Perceptron(MLP) neural network architecture

The steps to developing and implementing machine learning for these welding conditions adopted the PPDF routine defined below:

1. **Prepare** the welding process dataset
2. **Predict** the bead geometries for a set of input welding parameters using Python/SciKit-Learn.
3. **Display** the predicted bead geometries using Python/MatplotLib
4. **Format** the results in Excel spreadsheet using Visual Basic for Application (VBA)

The programming languages: Python and Visual Basic for Applications (VBA) have been proven to be valuable programming tools for data processing and machine learning within conventional Microsoft Excel. The prediction capabilities of the ANN developed within this work package provides the opportunity to be ported across other industrial sectors so long as quality-tabulated data is provided. The current limitation encountered within such applications involves the accuracy of the prediction (acceptable error function), this can be improved through the use of large datasets, suitably weighted coefficients and fine-tuning the hyper parameters of the ANN, e.g. number of neurons, number of layers and the learning rate.

It is important to note that the BOP and narrow groove weld joint configurations are treated as individual parts of the project. In this work package, the BOP melt run method was the main focus of attention due to the limited base material stocks and processing time available to produce the quantity of data needed for an accurate cross transfer assessment. To confidently adopt the inputs from the BOP form to directly predict the outputs for a multiple-pass "weld joint" configuration, an example being a single sided U-groove butt weld, was not possible due to the limited experimental data associated with such an arrangement. This latter arrangement requires the use of a 'staircase' weld profile to suitably stagger the weld layers in order to accurately assess the surface and volumetric conditions of the bead deposited.

Contents

1 Technical challenge and first principles

1.1 Background challenge

The **SIMPLE** project focused on developing a single manufacturing platform environment to assess the feasibility of combining multiple data sources, e.g. vision, acoustics and laser to determine a near to real-time inspection method to improve integrity and productivity. The process chosen to focus this combined data source capability utilised a Narrow Groove Gas Tungsten Arc Welding (GTAW) joint (1) due to the importance of welding recognised within the nuclear and other safety-critical manufacturing communities. This narrow groove butt joint configuration is the optimum profile to use for arc welding processes, adopted for joining thick-wall pipes and vessels of thicknesses greater than 50 mm. The general configuration of the welding layers and their notation is shown in Figure 1-1 (2). Narrow groove GTAW, although somewhat time consuming is far more efficient than conventional single-vee, double-vee and standard U-groove joints depicted within ISO 9692-1. However, the geometrical limits associated with acceptable aspect ratios determined by the flank angle, material thickness, and thermophysical properties combined with gas-metal reactions and metallurgical responses can potentially induce a variety of imperfections/defects e.g. lack of sidewall fusion, porosity, wormholes, lack of penetration and hydrogen cracking, etc.

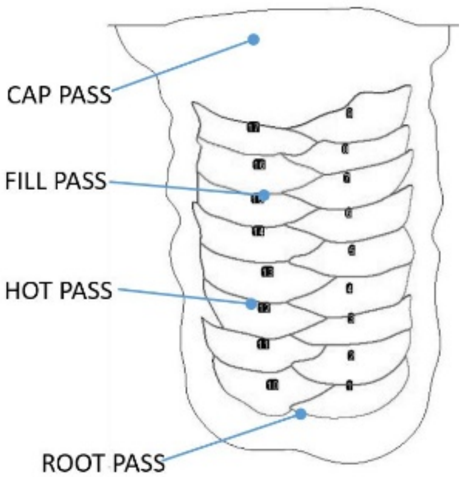


Figure 1-1: Narrow Groove Weld Joint

The selection of the welding parameters targeted to be adopted within the narrow groove joint was developed using the Bead-On-Plate (BOP) melt run method (3) (4). Baseline welding parameters were adopted using previous welding engineering experience in conjunction with BS EN 1011-2 and assessed to level C within BS EN ISO 5817:2014. The input welding parameters for the initial experimental phase would then be analysed through developing and using appropriate machine learning methods in order to predict the geometry of the deposited weld bead.

1.2 Present state-of-the-art

Machine learning (ML) is a data analysis technique that automates analytical model building. It is a branch of artificial intelligence founded on the idea that systems can learn from data, identify patterns and make autonomous decisions, or decisions with minimal human intervention. It can process large quantities of raw data from multiple sources.

Arc welding processes are one of the most common joining methods used within the nuclear and safety-critical manufacturing sectors. The complications associated with fusing metal within a local vicinity in a highly controlled manner produces complex interactive environments involving ionised plasma streams, liquid metal turbulence, gas-metal reactions, viscosity variance due to liquid-solid boundaries and solid-state phase transformation. Combining these variables with those essential processing variables makes predictions for bead geometries, and their respective interlayer relations, extremely difficult or near impossible without the use of ML systems. Traditional mathematical modelling, such as response surface methodology (5) and multiple regression (6), could be employed to meet the deliverables of this project and understand the input parameters for weld bead geometries. However, this project looks to investigate the application of ML models such as Artificial Neural Networks (ANNs) and how they can be deployed in manufacturing applications to best advantage. The advantage of using ANNs is their ability to predict the output of multiple interactive effects, use data from multiple sources and understand the interactions between welding variables and the effect on the fusion shape and profile of the deposited weld bead. ANN applicable to situations where multiple data inputs have a resultant output that is non-linear and not easily resolved using traditional approaches. Using appropriate weights (coefficients) can then be used to train the ANN to achieve an acceptable level of accuracy. There are several ANN architectures each with their own strengths and each using different principles in determining their own rules. A non-exhaustive list for this particular challenge include the Radial Basis Function (7), Back Propagation Neural Network (8), Multi-Layer Perceptron (MLP) (9). These kinds of technologies could be integrated with a suite of algorithms that may also be used for weld quality monitoring (10) and weld process optimisation (11). Through adopting these technologies in manufacturing, a significant reduction in the number of physical optimisation tests may be possible. This could dramatically improve the manufacturability of products leading to reduced lead-times and improved profitability.

State of the art in welding technology (3; 4; 5) combine welding robots and ML into a unified learning system that produce and predict key outputs. For example, the welding robot can autonomously gather welding bead geometry data using a laser scanner. The bead geometries and welding parameters are then automatically compiled into a database. Through ANN's, the robot learns from the database and eventually acquires the welding parameters and conditions to perform the welding operation without human intervention. This setup is presently only applied to BOP configurations. At present, there are no systems capable of learning and replicating those conditions that confidently predict optimum multiple bead deposits.

1.3 The technology

1.3.1 Artificial Neural Network (ANN)

ANN's are a mathematical modelling concept based upon how neurons in the human brain were originally assumed to function (12). Figure 1-2 shows one variant ANN architecture, a multilayer perceptron (MLP). The x values are the inputs to the model and the y values are the outputs of the model. The h values represent a set of 'hidden units' which define the model itself. These hidden units are composed of variables and non-linear functions which can be trained to make a given set of inputs approximate a given set of outputs. Each hidden layer can have an arbitrary number of hidden units.

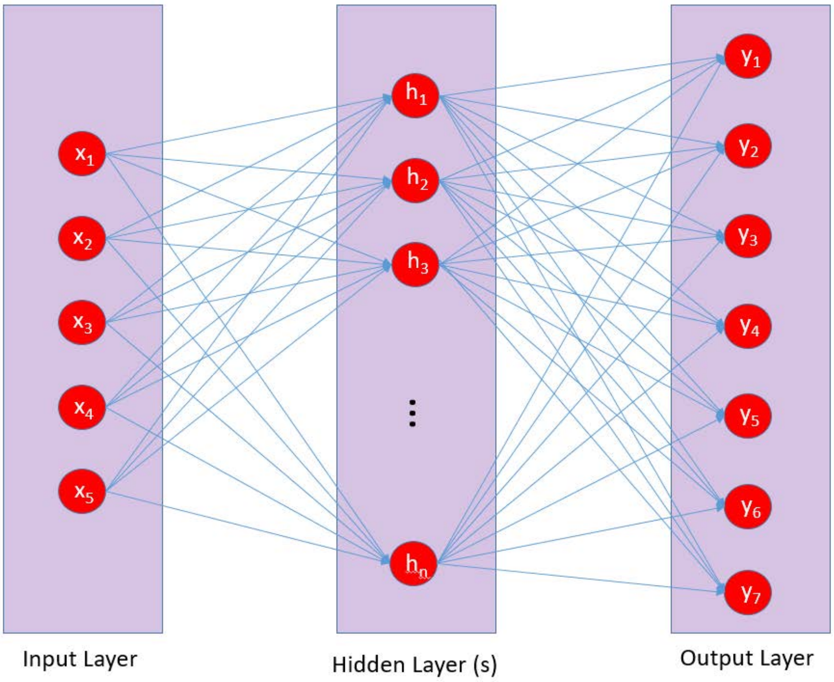


Figure 1-2: Multi-Layer Perceptron (MLP) Architecture

A MLP has at least 1 'hidden layer' between the input and output layers and is 'fully connected' (13). I.e. all nodes in a given layer are connected to every node in the adjacent layers. MLP's (as with other ANN's and machine learning algorithms) are typically used for classification or regression (14). Classification predicts a label (e.g. 'weld within tolerence') for a given set of inputs, whereas regression predicts a specific quantity (e.g. 10.2mm) for a given set of inputs.

A machine learning model is created by seperating a dataset into 3 parts: training, validation & testing (15). An ANN model is initially formed and optimised using the training data. Each time the model is used to make a prediction from a given set of inputs is referred to as the feed forward phase. Each modification to the model to adjust the output closer to the desired result is referred to as the backpropogation phase. One cycle of feed-forward and backpropagation is called one epoch. A number of epochs are performed until an acceptable performance is reached. The validation data is then used to further optimise the model on 'unseen' data by tweaking what are known as hyperparameters. Hyperparameters are user-selected variables of the model (e.g. the number of hidden units in a layer). Techniques such as k-fold cross validation can be used to combine the training and validation datasets, which is important when you have limited data (16). Testing data is then used only once to demonstrate the final performance of the model.

Further reading on ANN's can be done at various sources including (12; 13; 14; 17).

1.3.2 Weld modelling

Figure 1-3 shows the surface and fusion profile of a melt run/weld bead and some of the key geometrical aspects to be included in the model. Here, the green zone represents the weld's fusion and dilution area, and the red zone represents the Heat Affected Zone (HAZ).

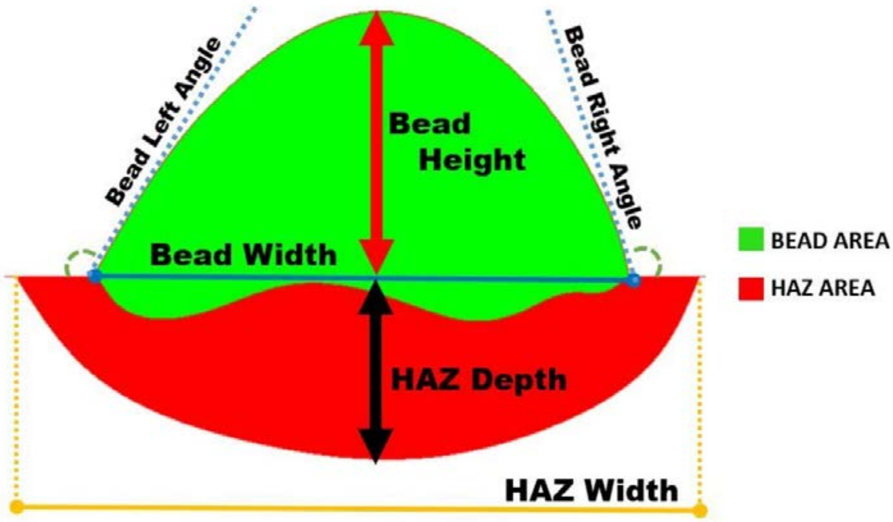


Figure 1-3: Bead Geometries

The list of input and output weld parameters is shown in Figure 1-4. The technical challenge within this work package is to predict the bead geometries for a BOP deposit and assess its direct transfer usage to a single narrow groove weld joint design for given input welding parameters. The pulse frequency was maintained at 2 Hz for all the bead on plate trials. i.e. pulsing between the high peak current and low background current.

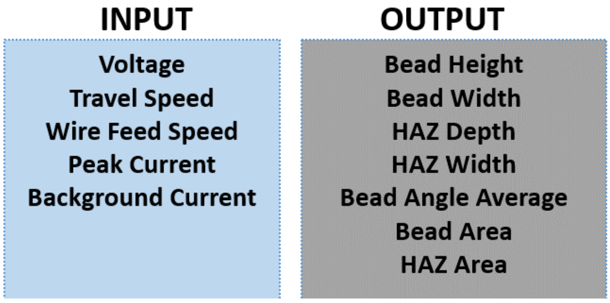


Figure 1-4: Welding Input Parameters and Bead Geometries

The parameters outlined in Figure 1-4 could be used within a generic ANN architecture as shown in Figure 1-5.

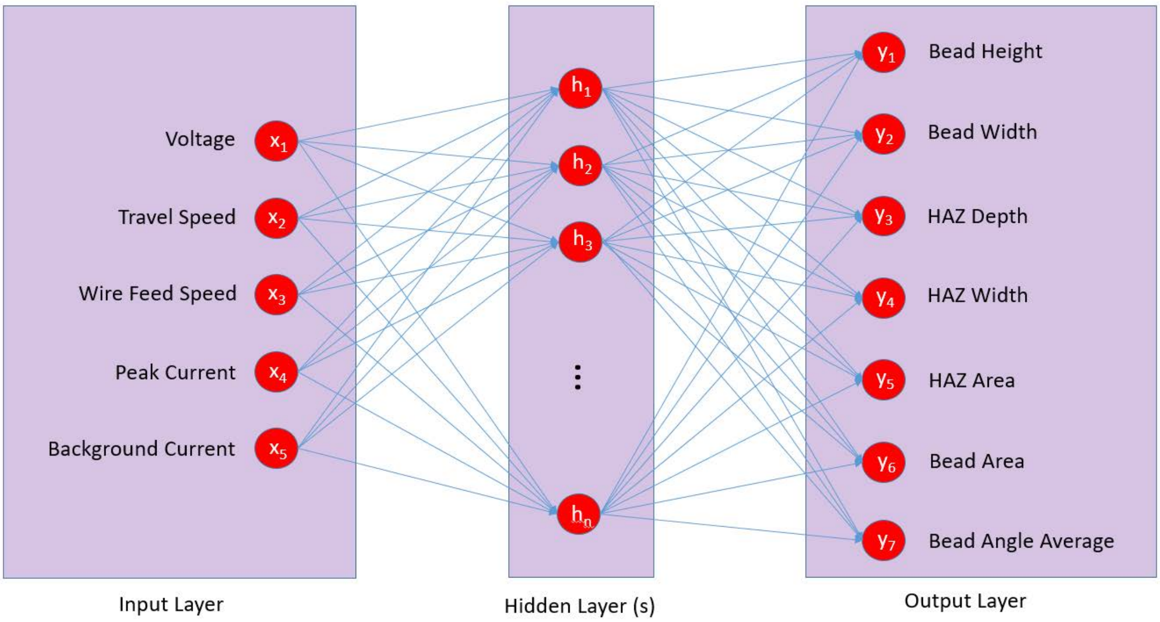


Figure 1-5: Specific Multi-Layer Perceptron Architecture

2 Starting MRL/TRL level

The Nuclear AMRC has adopted the manufacturing readiness and technology readiness level philosophy within this research programme as a methodology to identify levels of maturity, de-risk new ideas and progress achieved and future technology focused to contribute to demonstrating a 50% cost saving. The use of narrow groove weld joints utilising the gas-tungsten arc process as a vehicle to assess and predict the volumetric and surface integrity of a welded construction in near real-time.

Analysis of literature and existing capability associated with this technology determined that the TRL and MRL starting conditions for the BOP model satisfied approximately 80% - TRL 2 and 30% MRL 3 respectively – see Appendix 1.

3 Overview of technical challenge for industry

Evolution from first principles of weld modelling

3.1 Limitations of the technology

In welding simulation, Finite Element Analysis (FEA) adopting ABAQUS using FORTRAN as its preferred subroutine language is the most commonly used tool to predict the stresses and deformations of the welded component. The setup requires the user to define the input welding parameters such as electrical current and voltage, waveform, travel speed and gas chemistry to input into an ellipsoidal heat source model. The size of the weld bead, its fusion profile and dilution, is dependent on these and several more input conditions. Currently, there is no commercially available software capable of predicting and prescribing integrity outputs applied to a weld joint with multiple passes that can be directly generated from CAD models. This is due to the complex interactive relationship within and between the welding parameters, filler metal and base metal conditions under transient circumstances for varying joint designs. Successful multiple pass welding is often a trial-and-error exercise rather than an exact science, as it requires a considerable number of experiments to optimise processing conditions on a repeatable basis for a variety of variance emanating from base metal and filler metal chemistry variance through to changes in welding power source harmonics.

The industrial challenge was initially to determine the processing window to achieve a suite of weld bead aspect ratios (crown height to bead width ratio) that produced a toe angle (α) ≥ 135°, which conformed to level C within BS EN ISO 5817:2014. One possible solution is to use an ANN that utilises the MLP method for the BOP exercise to train the system to an acceptable level of error that predicts the bead geometries for a given set of welding parameters.

3.2 Potential applications

The MLP ANN method was deemed to be the most applicable to predict the bead geometry for a given set of welding parameters due to the benefits of efficiently distilling important patterns from each input. This makes the network analysis faster through identifying only important information and eliminating redundancy. Furthermore, the MLPs can accommodate techniques like backpropagation to determine the lowest level of error of a system through iteratively adjusting the weights between the input and output connections. The derivation and direct transfer of those welding parameters used for predicting the weld bead profile for a BOP configuration was deemed unsuitable to predict the outputs for a multiple pass welded joint. This is due to the additional complexities associated with metal ad-mixtures creating a greater level of material interaction accumulated from the sidewalls (joint flank) that skews the prediction.

3.3 Accuracy and confidence limitations

Within machine learning principles, the accuracy of prediction is highly dependent on the quantity and the quality of the input data (17). The dataset identified for the welding process and collected during the BOP experimental phase required a consistent technology baseline to work.

Within this work package all welding involved the gas-tungsten arc welding process, also known as TIG-141 (ISO 4063) and was conducted at the Nuclear AMRC using a Polysoude 600 PC system operating a narrow-groove NG 8-300 torch system (8 mm width x 300 mm depth) controlled by POW software.

3.4 Development path

The Figure 3-1 shows the development path for the work package.

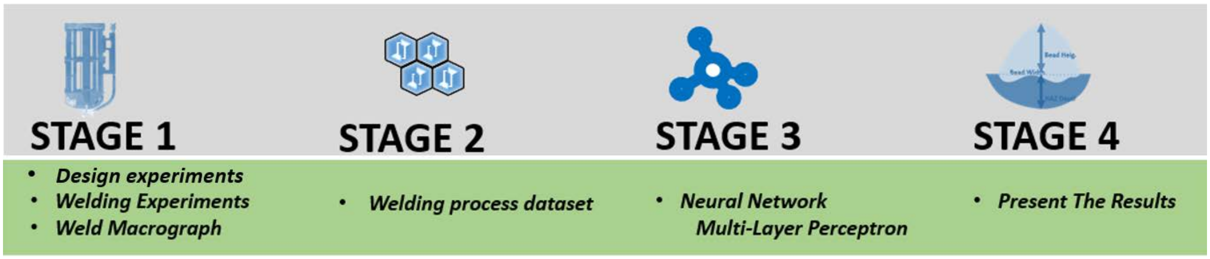


Figure 3-1: Development Path

The work done is described in the following staged description sections.

3.4.1 STAGE 1 – Determining the essential variables and output criteria

Design experiments

A systematic approach to data collection to ensure enough variance in the input and output parameters to create a useful model was required.

A design of experiments (DOE) was produced for this. A DOE is defined by boundary conditions which are the higher and lower limits of each of the selected test variables. The boundary conditions were selected from Nuclear AMRC welding engineer experience in working with the selected process and material.

1) Initially trials were carried out with Nuclear AMRC welding engineer experience to identify reasonable bead profiles. i.e weld height, weld width and no undercuts were considered. With these trials, got the bounding levels i.e. high, low and medium.

2) The high, low and medium parameters had been used to generate the DoE using MODDE.

3) The beads were analysed for their bead profile meeting the low toe angle, i.e > 120 deg. The toe angle greater than 120 deg would give a reasonable fusion in the side walls of groove welds i.e not much reinforcements on beads, reasonable width and shallow toe angle. With this criteria, 5 sets of parameters were selected from root pass, hot pass, fill pass, stringer cap pass and weave cap pass profile data to carry out groove welding trials.

Toe angle criteria, the ISO/British standard specifies:
1.BS EN ISO 5817: 2014, Welding – Fusion –welded joints in steel : Quality levels for imperfections.
2.BS EN ISO 6520-1: 2007, Welding and allied processes – Classification of geometric imperfections in metallic materials – Fusion welding.

The initial stage of assessment required a review of those essential variables for GTAW using table QW-256 of ASME BPVC Section IX: 2013.

Weld Experiments

The Nuclear AMRC then conducted BOP melt run experiments using a Polysoude 600 PC welding power source with a narrow-groove NG 8-300 torch.

The dataset compiled for the ANN consisted of 20 columns of parameters and 56 row of samples as shown in Figure 3-2 and Appendix A. These parameters have been subjected to several iterations prior to finalizing this template.

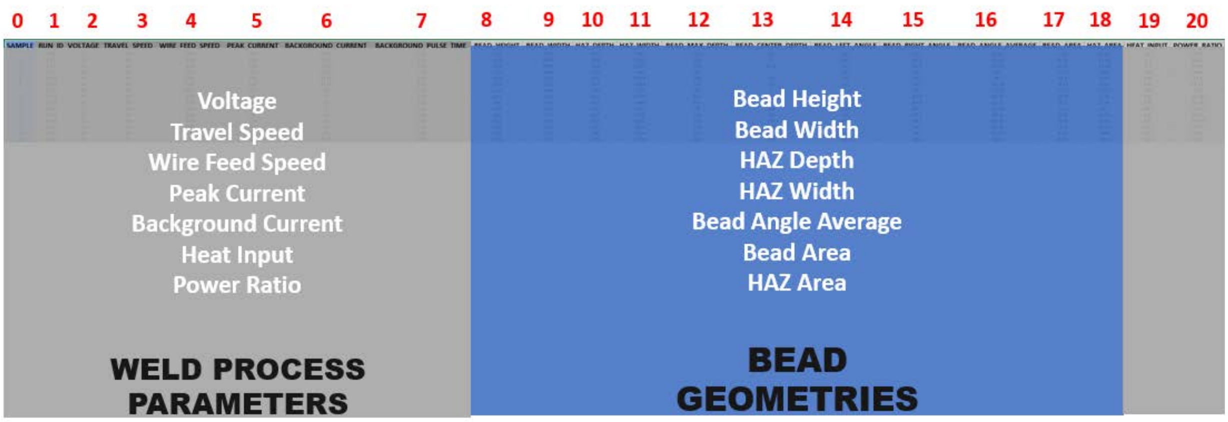


Figure 3-2: Weld Process Dataset (Seen in Appendix A)

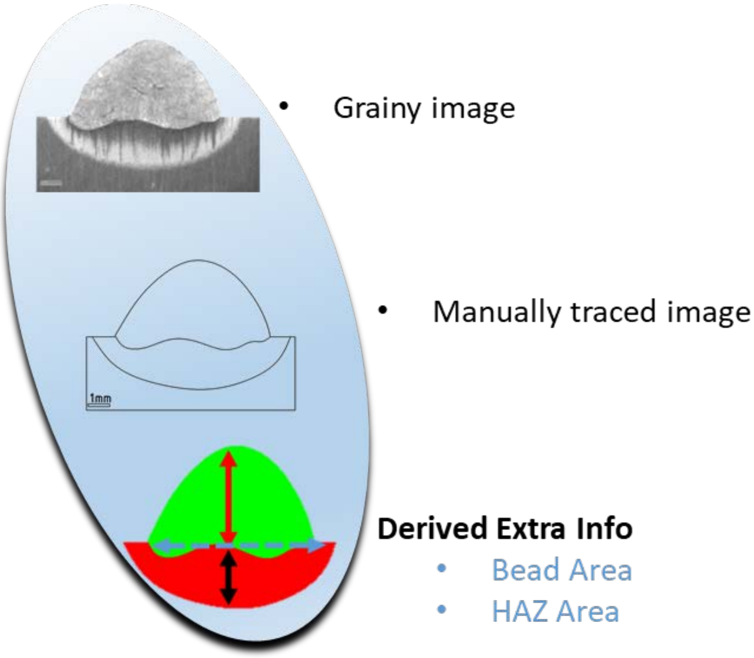


Figure 3-3: Weld Macrograph Improvement

The first step was to compile the bead geometry outputs, with seven key bead features to measure from macrographs taken. These encompassed: 1) Bead Height, 2) Bead Width, 3) Heat Affect Zone Depth, 4) Heat Affect Zone Width, 5) Bead Angle Average, 6) Bead Area and 7) Heat Affect Zone Area. Initially, these features were measured using optical microscopy, but were found to contain 'grainy' features that hindered the accuracy of the bead feature measurements. In order to improve macrograph image quality, the author manually traced the outline for all macrographs using ANSYS's SpaceClaim™ CAD package, which incorporated a scale bar to represent the relative size of the image. All traced images were imported into "ImageJ™" image processing software to extract the bead area and Heat Affected Zone Area (HAZ). In summary, the weld macrograph improvement is shown in Figure 3-3.

3.4.2 STAGE 2 – Data compilation

A total of 56 BOP melt run specimens were conducted using the Polysoude system, and each bead geometry and respective welding parameters were compiled as a CSV data set. This file is a prerequisite for the ML process.

As the dataset contained a wide range of units and magnitude, it was essential to 'data scale' them to a common denominator. This conversion was completed using the standard scale function within the SciKit-Learn™ Python package, a crucial step in the sequence. Standardisation and normalisation of the data in this way reduces the chance of unwanted behaviour in the model output (18). Figure 3-4 exhibits the before and after scaling outputs for all the parameters, where it shows that the magnitude of these parameters after data scaling, fall between -3 and 3 on the X-axis.

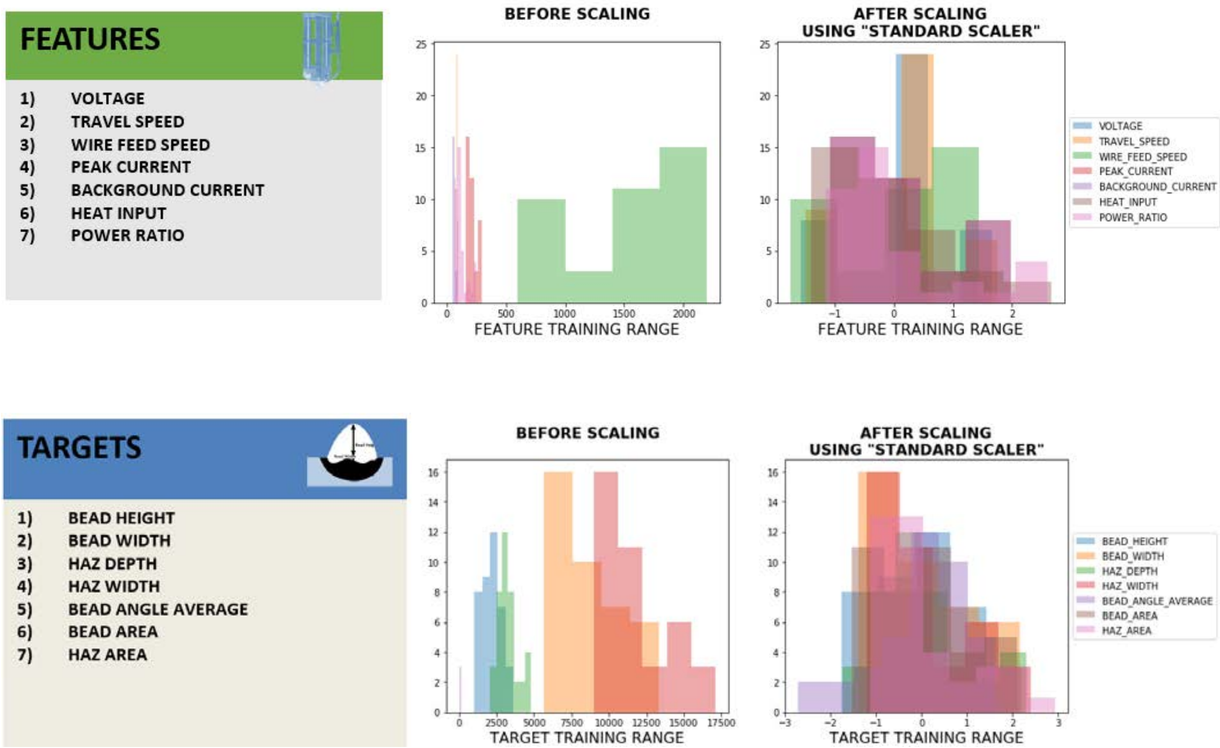
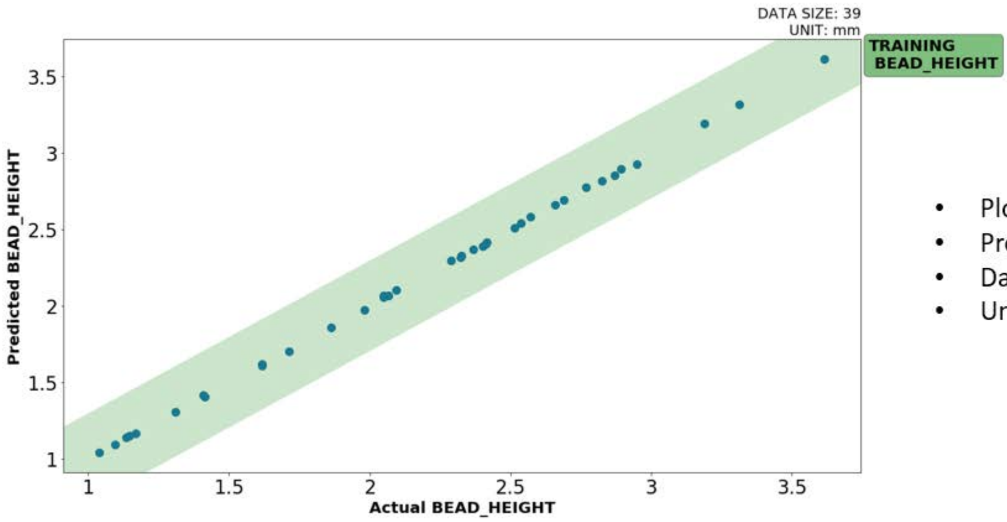


Figure 3-4: Welding Process Data Scaling

3.4.3 STAGE 3 – Model Development

Python programming model training

The main Python programming work is performed within this stage involving the use of the SciKit-Learn™ package and its "MLPRegressor" function to create, train and test the Multi-Layer Perceptron ANN. For this work package, the welding process dataset was apportioned 70% for training and 30% for testing. After running the ANN, predictions for bead geometries versus actual bead geometries were plotted using the Matplotlib™ Python package and a specified function plot. This function plotted the actual geometries in the X-axis and predicted geometries in the Y-axis. The top right hand corner of each plot has either "TRAINING" labelled with a green background as in Figure 3-5, or "TESTING" labelled with a purple background, as in Figure 3-6**,** which helped to differentiate the training/testing phases of the ML method. In addition, the "Data Size" label shows the size of the input data, and the "Unit" label shows the unit used in the plot. A wide green translucent linear band indicates the overall boundaries of the data. This plotting function has gone through an upgrade to handle the unit conversion from micrometre to the millimetre for the bead geometries.



- Plot using Matplotlib
- Predicted Vs Actual
- Data Size
- Unit

Figure 3-5: Predicted Vs Actual Bead Geometries [TRAINING]

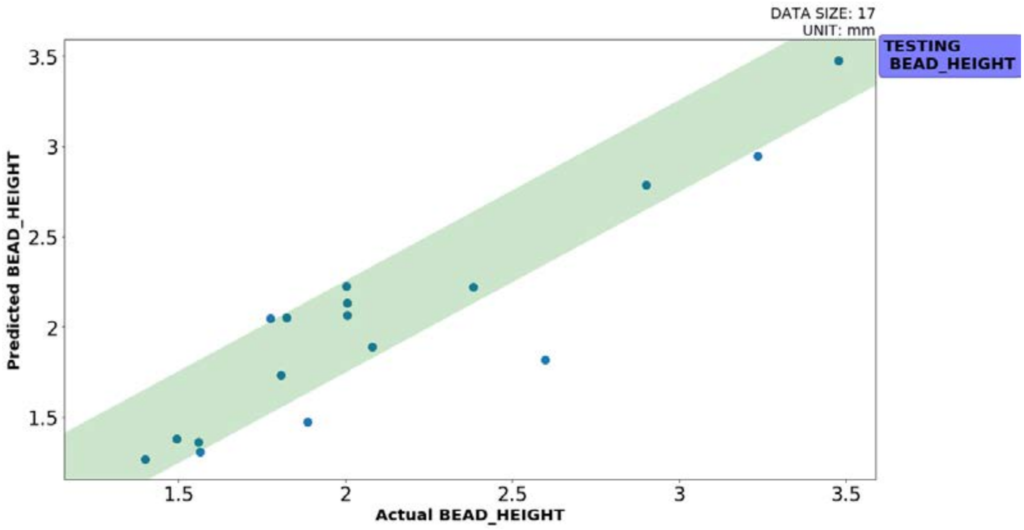
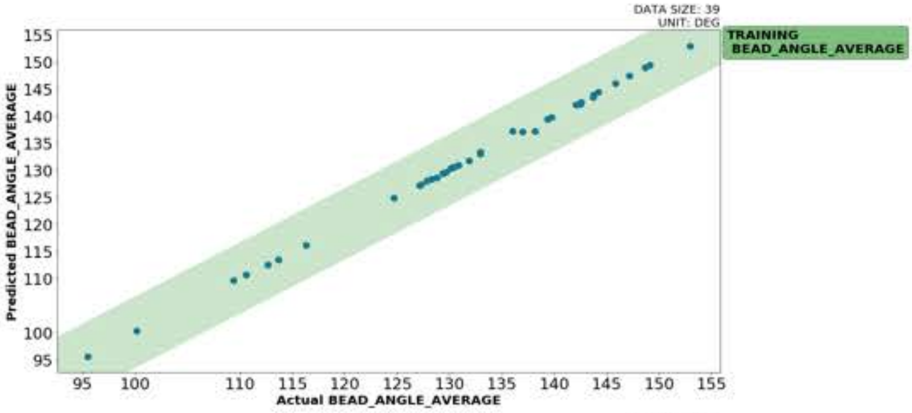
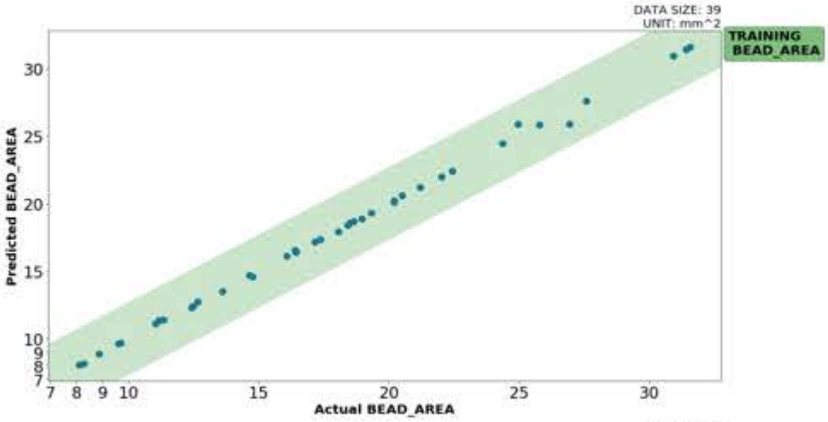


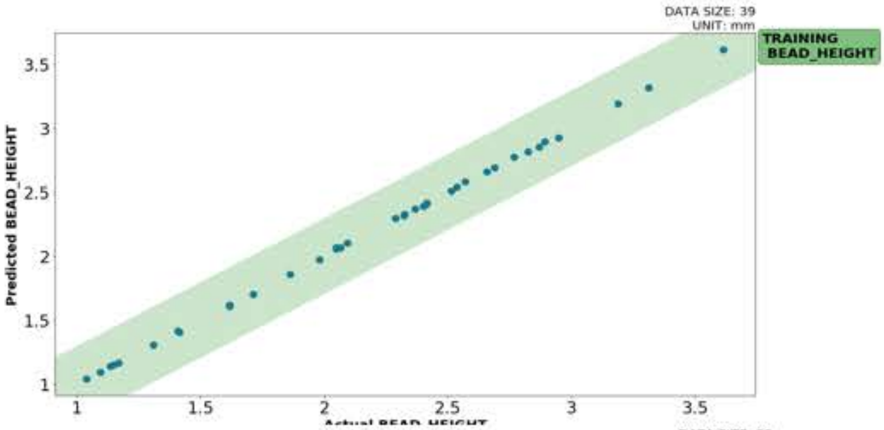
Figure 3-6: Predicted Vs Actual bead geometries [TESTING]

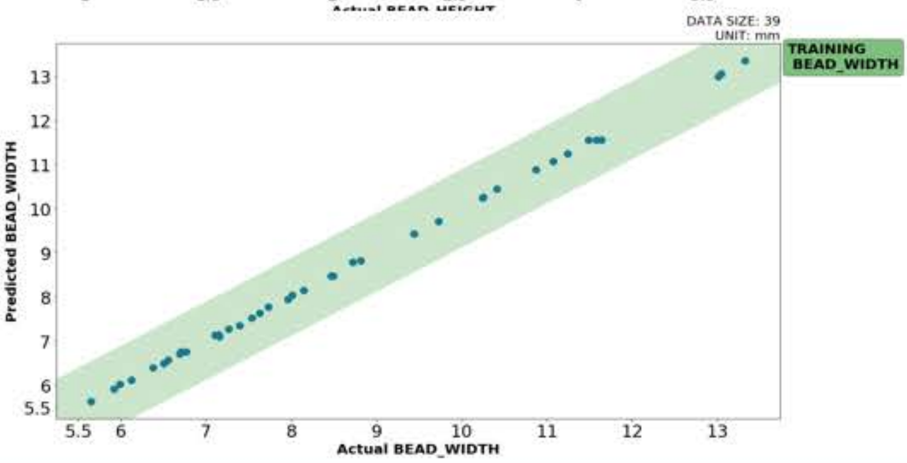
Training and predicting

Figure 3-7 shows all the plots of the predicted bead's geometries for the "training" phase of the neural network and as one would expect, it is not surprising that the predicted bead geometries fall within the linear straight line due to the direct measurement for a given input being closely correlated. Figure 3-8 shows the "testing" phase of the neural network; here there are discrepancies between the predicted and the actual geometries. Some of the data falls outside the green translucent boundary, which is due to the limited number of datasets used. More work is required to be done to modify the hyper parameters setting in the ANN to improve the accuracy of the bead geometries prediction.


DATA SIZE: 39
UNIT: DEG
TRAINING
BEAD_ANGLE_AVERAGE
Predicted BEAD_ANGLE_AVERAGE
Actual BEAD_ANGLE_AVERAGE


DATA SIZE: 39
UNIT: mm^2
TRAINING
BEAD_AREA
Predicted BEAD_AREA
Actual BEAD_AREA


DATA SIZE: 39
UNIT: mm
TRAINING
BEAD_HEIGHT
Predicted BEAD_HEIGHT


DATA SIZE: 39
UNIT: mm
TRAINING
BEAD_WIDTH
Predicted BEAD_WIDTH
Actual BEAD_WIDTH

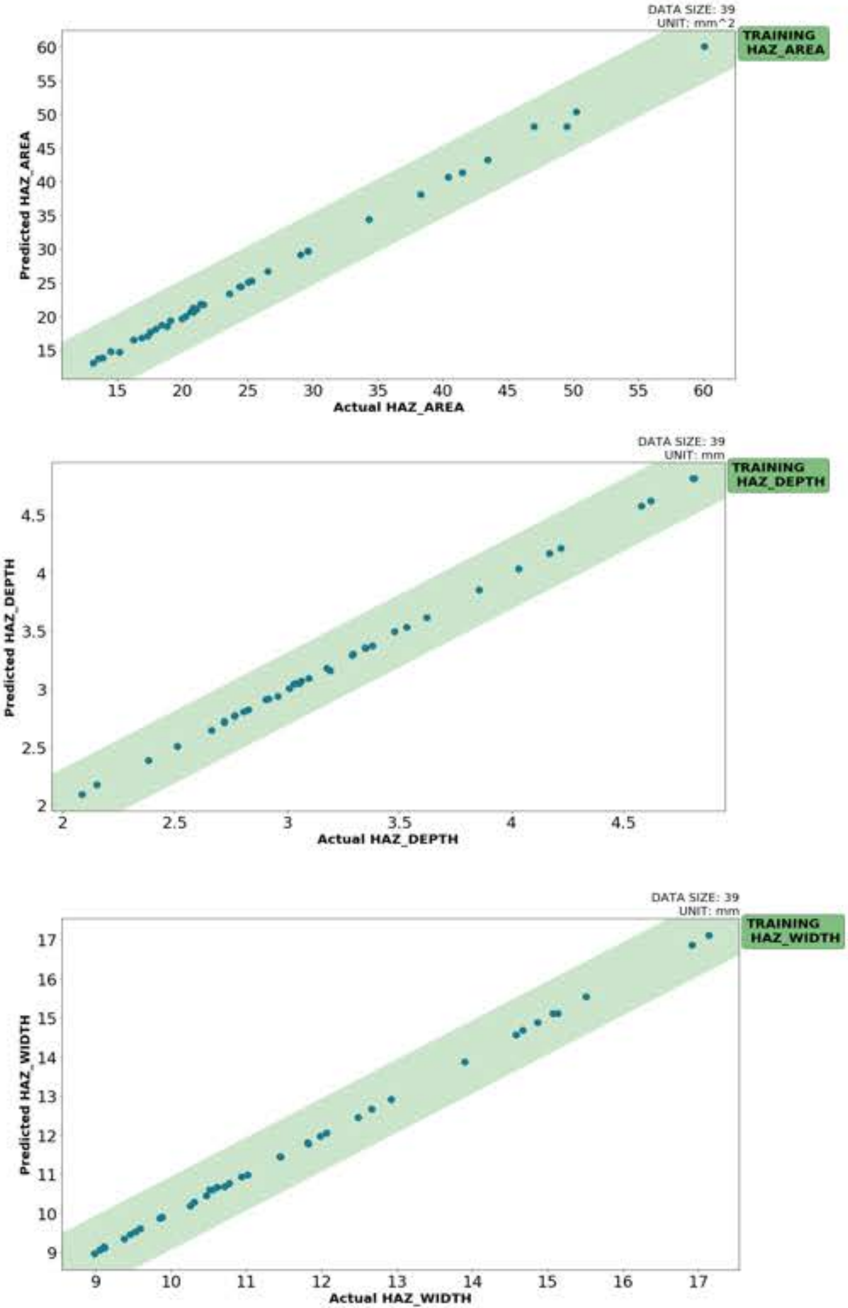
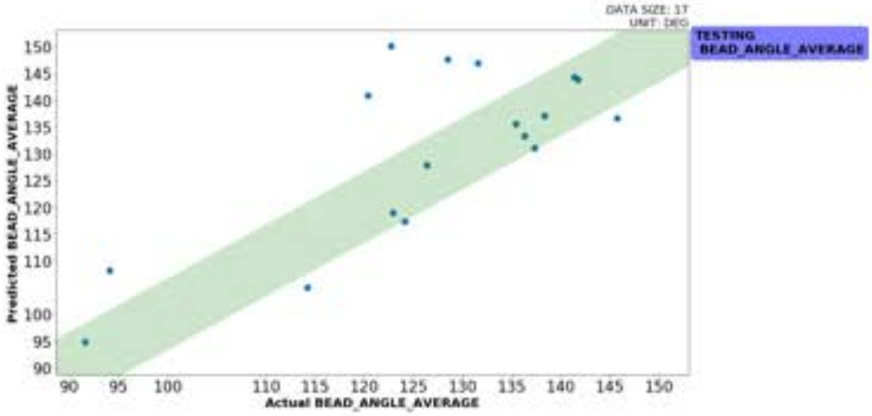
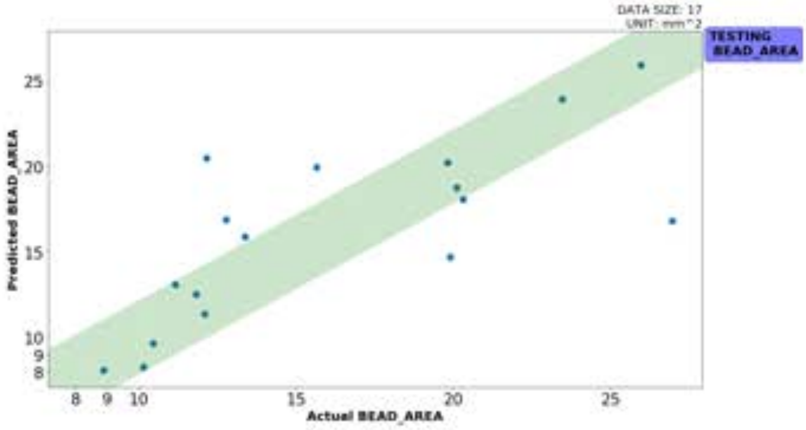
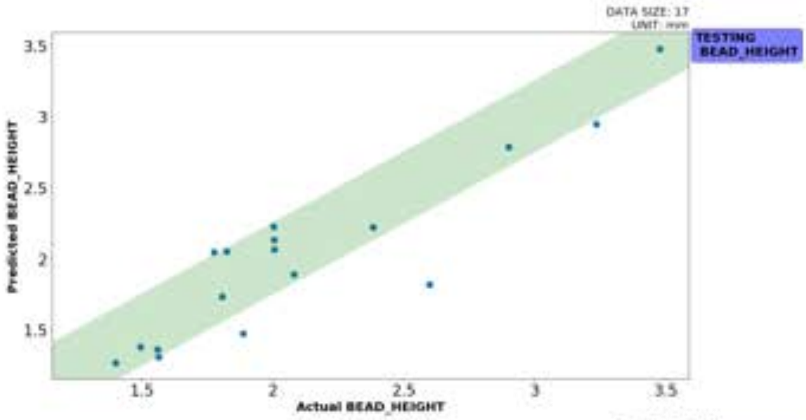
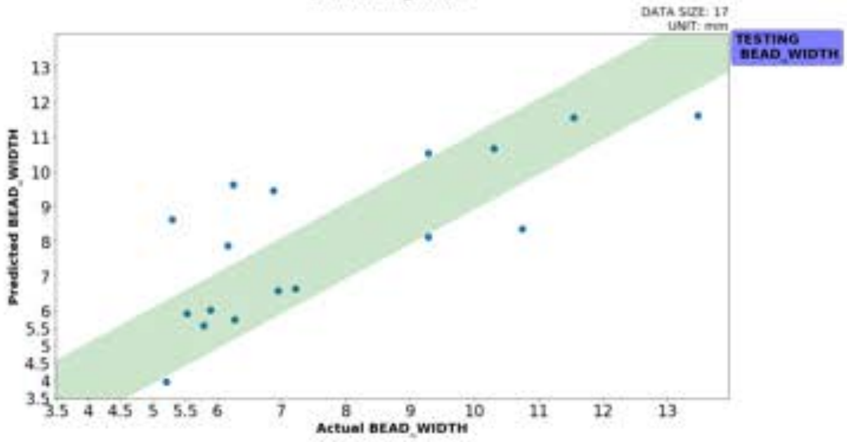


Figure 3-7: Plot of All Bead Geometries [TRAINING]


DATA SIZE: 17
UNIT: DEG
TESTING
BEAD_ANGLE_AVERAGE
Predicted BEAD_ANGLE_AVERAGE
Actual BEAD_ANGLE_AVERAGE


DATA SIZE: 17
UNIT: mm^2
TESTING
BEAD_AREA
Predicted BEAD_AREA
Actual BEAD_AREA


DATA SIZE: 17
UNIT: mm
TESTING
BEAD_HEIGHT
Predicted BEAD_HEIGHT
Actual BEAD_HEIGHT


DATA SIZE: 17
UNIT: mm
TESTING
BEAD_WIDTH
Predicted BEAD_WIDTH
Actual BEAD_WIDTH

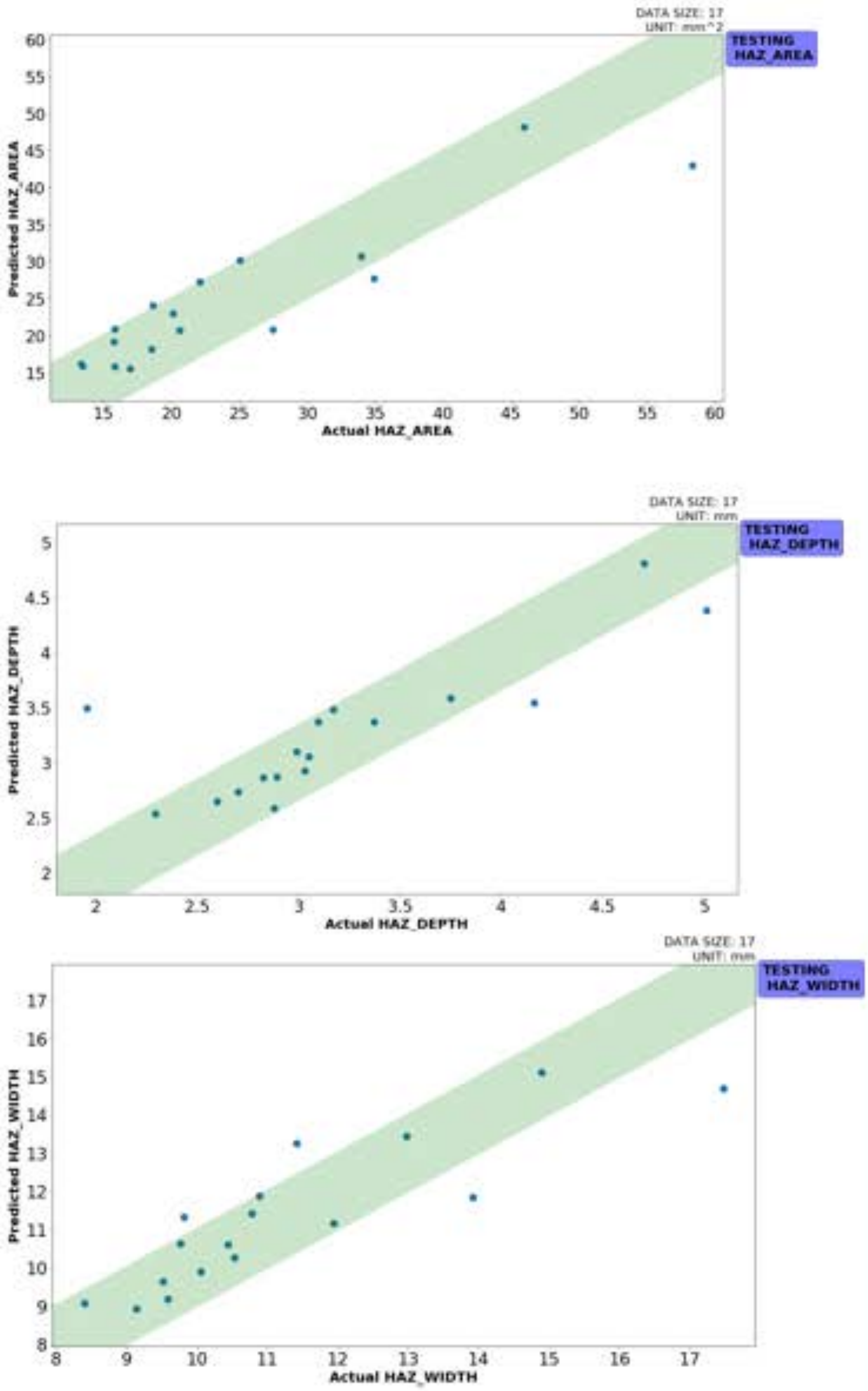
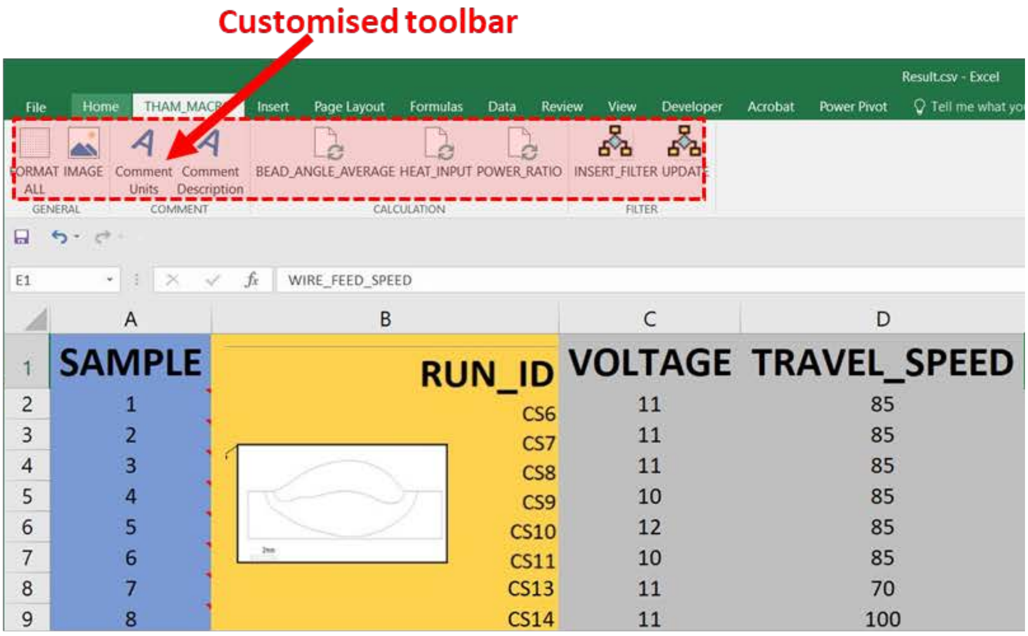


Figure 3-8: Plot of All Bead Geometries [TESTING]

3.4.4 STAGE 4 – Presenting the results

A customised macro was developed for enhancing the results of the modelling, this is shown in Figure 3-9. More detail can be seen in Appendix B.



A	B	C	D
SAMPLE	RUN_ID	VOLTAGE	TRAVEL_SPEED
1	CS6	11	85
2	CS7	11	85
3	CS8	11	85
4	CS9	10	85
5	CS10	12	85
6	CS11	10	85
7	CS13	11	70
8	CS14	11	100

Figure 3-9: Excel Customization – see Appendix A for detailed Excel data)

3.5 System considerations for future developments

Key points to aid future system developers working in the area of welding:

1. The level of effort needed to generate a suitable set of welding conditions formulated into a template capable of identifying a weighted ranking of ML inputs and outputs would save significant time and improve standardisation. The use of essential variables defined with the codes and standards is a fundamental starting point, but several complexities exist beyond their effective impact that can contribute to inducing processing perturbations, which manifest themselves as influencing factors during the evolution of a weld build. Therefore, the number of variables used for this work may need to be increased. The use of staggered or staircase profiles would aid in the derivation of each layer's input/output response during the build in order to assign a more confident reaction through optimising material usage and reducing extrapolation. However, it must be noted that simply reducing the weld length may incur a drop in statistical confidence along the complete joint length, which may be as a result of shrinkage, which reduces the joint width and changes the volume of flank material melted

2. The programming language requires familiarity of the syntax, availability of support documents and the add-on Statistical/Data Processing/ML packages available. One size does not fit all and the use of a decision generator to assign the most effective algorithm to choose the optimum neural network requires significant experience. The optimisation level (magnitude of error) using numerical calculations can be very expensive and the gradient descent, chaining, rectified linear units and backpropagation methods need to be carefully balanced for defining a system.

3. The use of Open Source ML software and the number of available algorithms provided a good baseline for the BOP melt run method, but extending this to the weld joint requires some innovative techniques incorporating a unified auxiliary package supported by a significant amount of test samples. Combining this in Python could also allow the use of data visualisation to determine the weld cross sectional area more accurately.

4 End MRL/TRL level

The ending TRL is 3 and MRL is 2 – see Appendix 1 for justification

4.1 Potential industrial impact

The Python script developed in this work package used an ANN to enable a confident prediction for BOP melt runs using those identified input welding parameters. However, this could not be confidently transferred to providing a solution for a narrow groove weld joint. The ability to predict the outputs of a multi pass weld as 'good' or 'bad', simply by inputting those welding conditions for a given joint profile and substrate chemistry requires a complex suite of ANN tools, backed up by a strong training programme. The MLP system could support this development due to the method's use of multiple hidden layer capability, but the predicted output values would not be able to provide the basis for 'prescribing' a solution. Here the use of genetic algorithms may be more suited.

The following are the possible usages and benefits of using the Python script developed:

- Engineers can predict the bead geometries of single pass butt welds or BOP melt runs for their required welding input parameters.
- The script provides a general interface that allows the welding dataset to be located on a company's server thus encouraging a culture of centralising all data in one known secure location and allowing it to be updated remotely.

4.2 Routes to impact

The Python script developed in this work package is not limited to welding applications. Due to the flexibilities of the Python programming language, its script can be extended to other manufacturing processes for ML. For example, in the area of machining, the script can be modified to predict the effect that machining parameters have on the quality of the machined surface, or for tool wear prediction. Experienced users can extend the functionalities of the script to handle statistical analysis, image processing and many more encompassing analytical and predictive capabilities. However, as such capabilities become multifarious requiring several hidden layers a compendium of ANNs will be required, with each one being suitably selected to handle a particular output to be optimised. Such a system will require an internal optimised engine generator based on a flexible coding/script platform.

4.3 Future Work

Large quantities of data are required for developing ML solutions to be effective in predicting processing outcomes. Image files, video, audio, laser scanner data, and processing acquisition information are also critical strands of data that can be formulated in creating this repository of key information. Developments in the science of big data, (i.e. systems that analyse, systematically extract information or deal with data sets that are too large or complex to be dealt with by traditional data-processing application software) will fundamentally underpin the next generation of predictive analytics, with a view to leading to prescriptive analytics. In the case of the welding process used within this package of work two crucial tasks, image processing and real-time data processing/visualisation need to be implemented in order to advance our understanding of the interaction of the welding parameters with that of the component or joint deformation. The following details have been proposed to enhance the capture and analysis of data to improve the depth of data and quality of the ANN.

4.3.1 Stepped Welding

The welding experiments conducted in this project were performed on a flat plate. Significant time was taken to complete the welding trials as the individual weld beads are layered across the complete length of the plate. A cost-saving solution to reduce consumable and base material used in the trials involves the use of “stepped welding” in a narrow groove on both flat plate and a cylindrical component. This is shown in Figure 4-1. This method can save significant processing and data capture time, as not all of the welding layer needs to be completed before the next layer of weld is added. By monitoring the evolution of the weld joint as it is built and the respective weld parameters, one can retrieve a large amount of data applicable to both fusion profiles, layer interaction and sidewall influences, in addition to the progressive deformation of the narrow groove geometry.

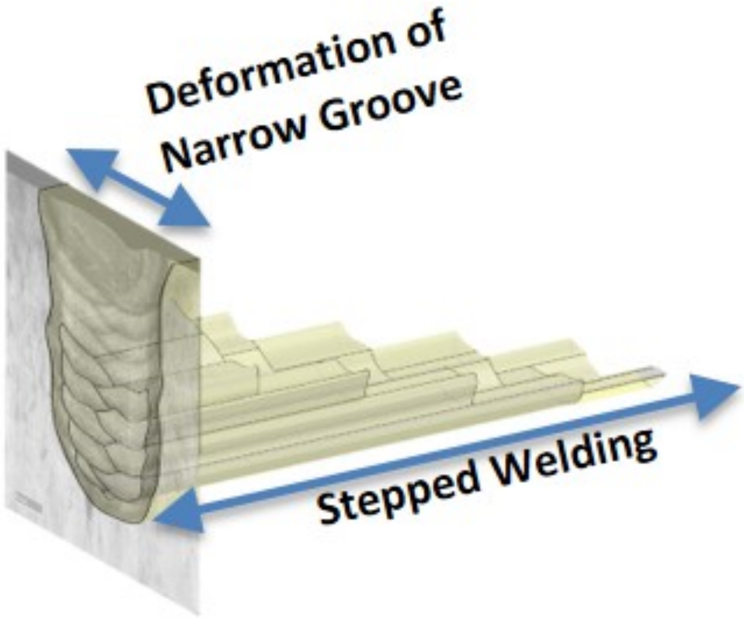


Figure 4-1: Staggered Welding

4.3.2 Image Processing of Weld Macrograph

For an ANN to work effectively, the user needs to have a robust technique to measure the weld bead geometry. Ideally, an image processing algorithm should be used to extract the weld bead surface and fusion profiles from the weld bead macrograph as shown in Figure 4-2. Within the metallographic strand of work completed by the Nuclear AMRC these measurements were manually performed using optical microscopy. The weld bead measurements were then manually entered into the Excel spreadsheet. Although image analysis programs, such as "ImageJ ™" developed by the National Institute of Health could be used to measure these profiles it is still a manually operated task with the software limited in image recognition capability. OpenCV™ (Open Source Computer Vision) software has this functionality and more, with the capability to offer real-time image processing for detecting the contours of the weld bead; features such as bead width, bead height are identifiable without any human intervention. Furthermore, issues such as image contrast and brightness do not impact on the accuracy. Together with the customised VBA scripts already developed in this work package, bead dimensions can be imported into an Excel spreadsheet.

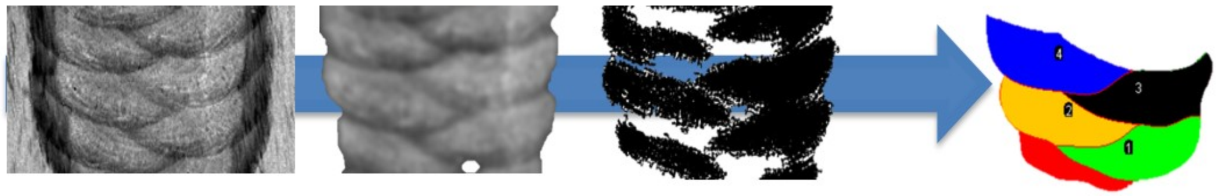


Figure 4-2: Image Processing from actual image through to binary and erosion

4.3.3 Data Visualisation: Real time weld build acquisition

Welding engineers ideally need to be able to visualise the evolution of the weld build that corresponds to the respective welding conditions used at that stage in the process to assess the feasibility of a deposited layer being classified as acceptable or out of specification. The best orientation to visualise the weld bead build-up is in a 2D cross-sectional view, as shown in Figure 4-3. This allows the engineer to understand how much filler material has been deposited for the bead and its position relative to the groove boundary at a given timeframe. By combining real-time image processing and ML, one can identify if any anomalies are likely to occur during the build-up by correlating the image with the respective welding process parameters used.

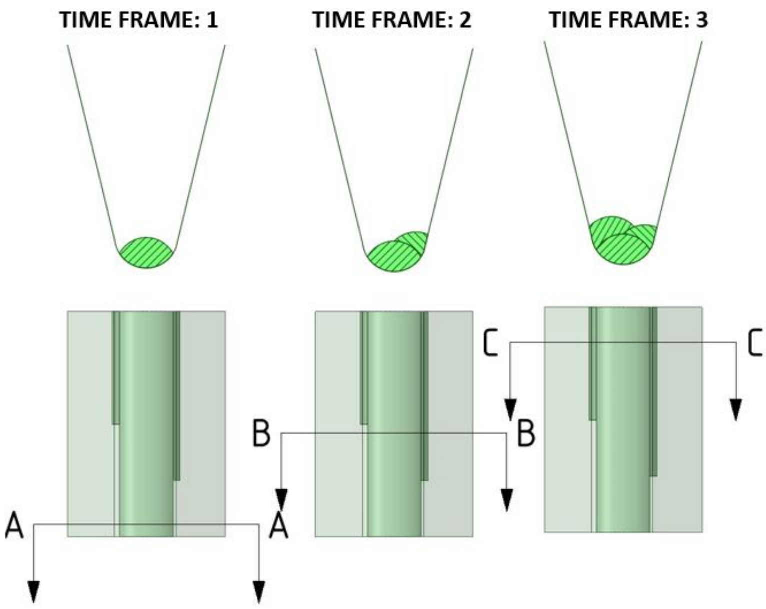


Figure 4-3: Data Visualization

5 Recommendation for further research and development

5.1 Decisions and future opportunities for improvement

The BOP configuration prediction, whilst suitable for a baseline to adopt for surfacing techniques, does face considerable difficulty in order to be morphed into a multiple pass predictive tool. However, the author proposes that with sufficient data produced from using a staggered or staircase welding sequence it should be possible to develop a confident statistical model. The statistical model will need to use the MLP method by adopting a deep neural network that captures those interactive variables from within the joint, e.g. volume of sidewall melting and positioning and angle of welding torch, the prediction confidence to determine the integrity of such a configuration should be possible.

Welding Dataset

It was deemed imperative to have a dataset file for those essential welding variables, and have this made available and easily viewed in any text editor and spreadsheet. The compilation of the dataset depends on the outputs from the welding experiments and macrograph analysis to generate the initial 'feed forward' network whilst ascribing the suitable activation functions.

The future opportunity here would be through improving the throughput compilation of the bead geometries, due to this being a time consuming measurement process being completed by human operators. Ideally, a dedicated image processing system (a new machine learning ANN system) would be ideal to automatically measure these geometrical features and populate these within a workable repository system. This would streamline the data collection task.

Programming Language

The software tool for ML falls into either Commercial or Open Source. Commercial packages, such as MATLAB™ and SAS™, have access to up-to-date ML modules and technical support. For tailored features, technical support is either not possible due to the high development cost or lack of business motivation to develop them. For this reason, Open Source software such as Tensorflow™, Scikit-Learn™, Keras™, Torch™, Caffe™, and Theano™ are alternative choices.

The motivation for using Open Source is the flexibility to create tailored in-house ML algorithms to handle complex ML requirements. Open Source codes are supported globally via independent developers and online forums dedicated to ML applications. The disadvantages of using Open Source is the need to devote a considerable amount of resources to maintain these codes in-house and their openness to being used by all interested parties, which leaves the IP non-existent.

The Nuclear AMRC selected SciKit-Learn™ as the ML package for this work because it contains many standard ML algorithms that offer tools ML users need. Furthermore, it is well documented with numerous examples.

The opportunity to use TensorFlow™ software developed by Google would be needed to develop deep learning ANNs for multiple pass weldments. The use of TensorFlow™ to develop the algorithm for predicting the bead shape and fusion zone for the BOP work package was deemed an overkill due to the welding dataset being so small.

5.2 The Route to Industrial Adoption

The integration of ML into everyday manufacturing development programmes can provide a powerful device, either as an individual / stand-alone engineering tool or combined within a "One-Stop" digital service for the industry via accessing Cloud Based data services for data sharing, retrieving, predicting, and visualizing processing data.

The implementation of the proposed service is shown in Figure 5-1. The beneficial point for the Nuclear AMRC and the UK supply-chain is the opportunity for such a system to offer a direct line of information to accelerate solutions. Such a system could provide information solutions covering many specialised and advanced fabrication processes. The full spectrum of optical sensors, laser scanners, acoustic and welding data acquisition systems should be deployed to ensure the highest standard of quality is met through the capture of detailed data, and exercising of predictive analytics. This "One-Stop" service would seem to appeal to manufacturers and customers operating in the oil and gas, marine, automotive, aerospace sectors etc.

There are several strategies to implementing this digital service. From generating the welding data in-house to franchising the data analysis to external solution providers. One possible way forward could be a collaborative approach with industrial customers to understand their welding needs to maximize the impact this digital service provides, and to uncover other niche services.

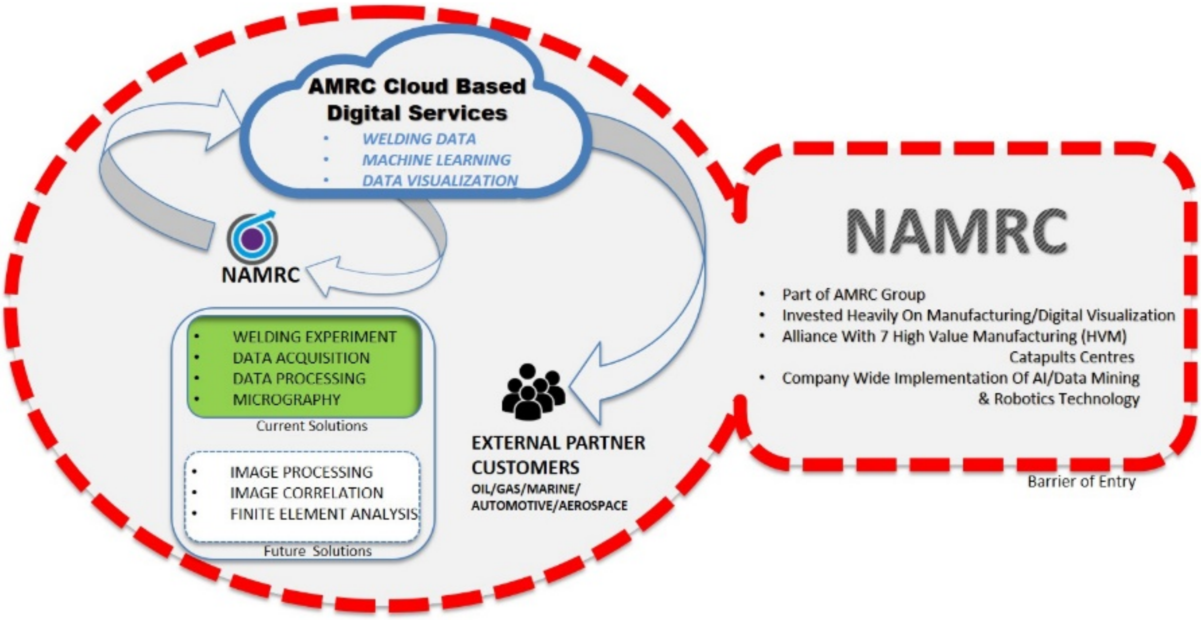


Figure 5-1: Commercialization of Weld Bead Prediction

5.3 Engagement with industry/academia

ML and ANNs are areas of advanced digital systems development. These are state of the art technologies, which will revolutionise industry business culture and its operations. ML can process vast quantities of data and perform complex real-time analysis, enabling companies to explore new ideas and generate innovative solutions significantly quicker.

The Nuclear AMRC is focused on nuclear and other large-scale related products and services. It is keen to engage with organizations and industries to develop and use Big Data for “spin off” technology opportunities to benefit the AMRC group, its partners and the UK supply-chain.

The work done in Work package 2.1: ‘Weld Process Modelling’ demonstrates how the use of ML to make predictions from raw data is a good foundation for industrial engagement and research ventures. The author proposes a one-day seminar to promote the use of ML to small medium enterprises. This seminar is not confined to just welding applications, but any companies can gain an appreciation of ML applications. In this event, Nuclear AMRC can provide free and impartial advice on ML implementations. Beside this, the seminar will have a 1-hour breakout session for participant to meet with Nuclear AMRC’s Technical Leads in the areas of simulation, metrology and machining to discuss other technical needs. From this event, Nuclear AMRC will generate supporting case studies for future CR&D bidding needs, and strengthen the link between universities and the industry.

References

1. **Polysoude.** *The art of welding: narrow gap TIG welding handbook.* s.l. : Polysoude,Nantes,France, 2013.

2. *A study on the effect of weld groove designs on residual stresses in SS 304N thick multipass pipe welds.* **A. Giri, M. M. Mahapatra, K. Sharma, P. K. Singh.** 1, 2017, International Journal of Steel Structures , Vol. 17, pp. 65-75.

3. *Neural network modeling for prediction of weld bead geometry in laser microwelding.* **Mohd Idris Shah Ismail, Yasuhiro Okamoto, Akira Okada.** 2013, Advances in Optical Technologies, pp. 1-7.

4. *Prediction of weld bead geometry and penetration in shielded metal-arc welding using artificial neural networks.* **D.S. Nagesh, G.L. Datta.** 2002, Journal of Materials Processing Technology, Vol. 123, pp. 303-312.

5. *Effect of laser welding parameters on the heat input and weld-bead profile.* **K.Y. Benyounis, A.G. Olabi, M.S.J. Hashmi.** 2005, Journal of Materials Processing Technology, Vols. 164-165, pp. 978-985.

6. *Modeling of tig welding process by regression analysis and neural network technique.* **Randhir Kumar, Sudhir Kumar Saurav.** 10, 2015, International Journal of Mechanical Engineering and Technology, Vol. 6, pp. 10-27.

7. *Sensor based weld bead geometry prediction in pulsed metal inert gas welding process through artificial neural networks.* **Sukhomay Pal, Surjya K. Pal, Arun K. Samantaray.** 2008, International Journal of Knowledge-Based and Intelligent Engineering Systems, pp. 1-14.

8. *A comparison of two types of neural network for weld quality.* **Xiaodong Wan, Yuanxun Wangb, Dawei Zhao, YongAn Huang.** 2017, Mechanical Systems and Signal Processing, Vol. 93, pp. 634-644.

9. *Through-thickness residual stress profiles in austenitic stainless steel welds: a combined experimental and prediction study.* **J. MATHEW, R.J. MOAT, S. PADDEA, J.A. FRANCIS, M.E. FITZPATRICK, P.J. BOUCHARD.** 2017, METALLURGICAL AND MATERIALS TRANSACTIONS A, Vol. 48A, pp. 6178-6191.

10. *Weld quality monitoring research in small scale resistance spot welding by dynamic resistance and neural network.* **Xiaodong Wan, Yuanxun Wang, Dawei Zhao, YongAn Huang, Zhouping Yin.** 2017, Measurement, pp. 120-127.

11. *Welding process optimization with artificial neural network applications.* **Adnan Aktepe, Suleyman Ersoz, Murat Luyy.** 14, 2014, Neural Network World, Vol. 6, pp. 655-670.

12. *Neural networks and statistical techniques: A review of applications.* **Mukta Paliwal, Usha A. Kumar,.** 1, s.l. : Expert Systems with Applications, 2009, Vol. 36. ISSN 0957-4174, https://doi.org/10.1016/j.eswa.2007.10.005.

13. **Csáji, Balázs Csanád.** *Approximation with Artificial Neural Networks - MSc thesis.* Hungary : Eötvös Loránd University, 2001.

14. *Logistic regression and artificial neural network classification models: a methodology review.* **Stephan Dreiseitl, Lucila Ohno-Machado.** 5–6, s.l. : Journal of Biomedical Informatics, 2002, Vol. 35. ISSN 1532-0464,https://doi.org/10.1016/S1532-0464(03)00034-0.

15. **Training set vs. Test set vs. Validation set – what´s the deal? *Machine Learning, Deep Learning, AI - Tutorials.* [Online] 01 04 2017. [Cited: 11 09 2019.] https://www.machinelearningtutorial.net/2017/04/01/training-set-vs-test-set-vs-validation-set-whats-the-deal/.**

16. Raschka, Sebastian. *Model Evaluation, Model Selection, and Algorithm Selection in Machine Learning.* s.l. : Cornell University, 2018. arXiv:1811.12808.

17. *Efficient Machine Learning for Big Data: A Review.* Omar Y. Al-Jarrah, Paul D. Yoo, Sami Muhaidat, George K. Karagiannidis, Kamal Taha. s.l. : Big Data Research, 2015, Vol. 2. DOI: http://dx.doi.org/10.1016/j.bdr.2015.04.001.

18. *Importance of input data normalization for the application of neural networks to complex industrial problems.* Sevilla, J. Sola and J. s.l. : IEEE Transactions on Nuclear Science, 1997, Vol. 44. doi: 10.1109/23.589532.

19. *Application of artificial neural network for predicting weld quality in laser transmission welding of thermoplastics.* Bappa Acherjeea, Subrata Mondalb, Bipan Tuduc, Dipten Misrab. 2011, Applied Soft Computing, Vol. 11, pp. 2548-2555.

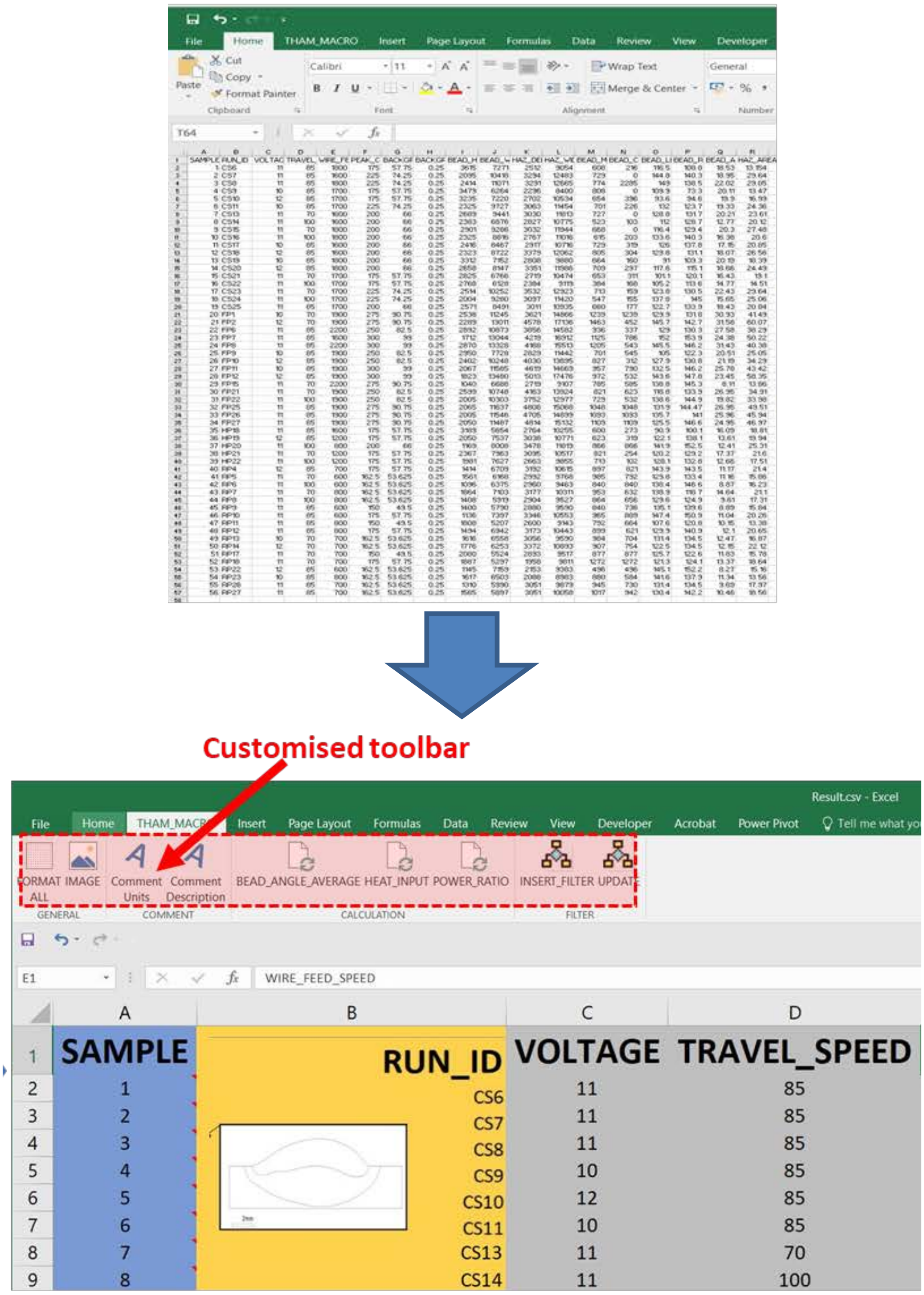
Appendix A – Weld Process Data

SAMPLE	RUN_ID	VOLTAGE	TRAVEL_SPEED	WIRE_FEED_SPEED	PEAK_CURRENT	BACKGROUND_CURRENT	BACKGROUND_PULSE_TIME	BEAD_HEIGHT	BEAD_WIDTH	HAZ_DEPTH	HAZ_WIDTH	BEAD_MAX_DEPTH	BEAD_CENTER_DEPTH	BEAD_LEFT_ANGLE	BEAD_RIGHT_ANGLE	BEAD_ANGLE_AVERAGE	BEAD_AREA	HAZ_AREA	HEAT_INPUT	POWER_RATIO
1	CS6	11	85	1800	175	57.75	0.25	3615	7271	2512	9054	608	216	116.5	108.8	112.65	18.53	13.154	0.54	76.97
2	CS7	11	85	1600	225	74.25	0.25	2095	10418	3294	12483	729	0	144.8	140.3	142.55	18.95	29.64	0.7	111.33
3	CS8	11	85	1800	225	74.25	0.25	2414	11071	3291	12665	774	2285	149	138.5	143.75	22.02	29.05	0.7	98.96
4	CS9	10	85	1700	175	57.75	0.25	3479	6264	2296	8400	808	0	109.9	73.3	91.6	20.11	13.47	0.49	74.09
5	CS10	12	85	1700	175	57.75	0.25	3235	7220	2702	10534	654	396	93.6	94.6	94.1	19.9	16.99	0.59	88.9
6	CS11	10	85	1700	225	74.25	0.25	2325	9727	3063	11454	701	226	132	123.7	127.85	19.33	24.36	0.63	95.25
7	CS13	11	70	1600	200	66	0.25	2689	9441	3030	11813	727	0	128.8	131.7	130.25	20.21	23.61	0.75	81.5
8	CS14	11	100	1600	200	66	0.25	2383	6876	2827	10775	523	103	112	128.7	120.35	12.77	20.12	0.53	116.42
9	CS15	11	70	1800	200	66	0.25	2901	9286	3032	11944	668	0	116.4	129.4	122.9	20.3	27.48	0.75	72.44
10	CS16	11	100	1800	200	66	0.25	2325	8816	2767	11016	615	203	133.6	140.3	136.95	16.38	20.6	0.53	103.49
11	CS17	10	85	1600	200	66	0.25	2416	8467	2917	10716	729	319	126	137.8	131.9	17.15	20.85	0.56	89.96
12	CS18	12	85	1600	200	66	0.25	2323	8722	3379	12062	805	304	129.8	131.1	130.45	18.07	26.56	0.68	107.95
13	CS19	10	85	1800	200	66	0.25	3312	7152	2808	9880	664	160	91	109.3	100.15	20.19	18.39	0.56	79.97
14	CS20	12	85	1800	200	66	0.25	2658	8147	3351	11986	709	297	117.6	115.1	116.35	18.66	24.49	0.68	95.96
15	CS21	11	70	1700	175	57.75	0.25	2825	6766	2719	10474	653	311	101.1	120.1	110.6	16.43	19.1	0.66	67.11
16	CS22	11	100	1700	175	57.75	0.25	2768	6128	2384	9119	384	168	105.2	113.6	109.4	14.77	14.51	0.46	95.88
17	CS23	11	70	1700	225	74.25	0.25	2514	10252	3532	12923	713	159	123.8	130.5	127.15	22.43	29.64	0.85	86.29
18	CS24	11	100	1700	225	74.25	0.25	2004	9280	3097	11420	547	155	137.8	145	141.4	15.65	25.06	0.59	123.27
19	CS25	11	85	1700	200	66	0.25	2571	8491	3011	10935	660	177	122.7	133.9	128.3	18.43	20.84	0.62	93.14
20	FP1	10	70	1900	275	90.75	0.25	2538	11245	3621	14866	1239	1239	129.9	131.8	130.85	30.93	41.49	0.94	85.78
21	FP2	12	70	1900	275	90.75	0.25	2289	13011	4578	17136	1463	452	145.7	142.7	144.2	31.58	60.07	1.13	102.94
22	FP6	11	85	2200	250	82.5	0.25	2892	10873	3856	14582	936	337	129	130.3	129.65	27.58	38.29	0.77	89.96
23	FP7	11	85	1600	300	99	0.25	1712	13044	4219	16912	1125	786	152	153.9	152.95	24.38	50.22	0.93	148.44
24	FP8	11	85	2200	300	99	0.25	2870	13328	4168	15513	1205	543	145.5	146.2	145.85	31.43	40.38	0.93	107.95
25	FP9	10	85	1900	250	82.5	0.25	2950	7728	2829	11442	701	545	105	122.3	113.65	20.51	25.05	0.7	94.7
26	FP10	12	85	1900	250	82.5	0.25	2402	10248	4030	13895	827	312	127.9	130.8	129.35	21.19	34.29	0.84	113.64
27	FP11	10	85	1900	300	99	0.25	2067	11585	4619	14669	957	790	132.5	146.2	139.35	25.78	43.42	0.84	113.64
28	FP12	12	85	1900	300	99	0.25	1823	13480	5013	17476	972	532	143.6	147.8	145.7	23.45	58.35	1.01	136.36
29	FP15	11	70	2200	275	90.75	0.25	1040	6688	2719	9107	785	585	138.8	145.3	142.05	8.11	13.86	1.03	81.5
30	FP21	11	70	1900	250	82.5	0.25	2599	10748	4163	13924	821	623	118.8	133.9	126.35	26.95	34.91	0.94	85.78
31	FP22	11	100	1900	250	82.5	0.25	2005	10303	3752	12977	729	532	138.6	144.9	141.75	19.82	33.98	0.66	122.55
32	FP25	11	85	1900	275	90.75	0.25	2065	11637	4808	15068	1048	1048	131.9	144.47	138.185	26.95	49.51	0.85	114.58
33	FP26	11	85	1900	275	90.75	0.25	2005	11546	4705	14899	1093	1093	135.7	141	138.35	25.96	45.94	0.85	114.58
34	FP27	11	85	1900	275	90.75	0.25	2050	11487	4814	15132	1109	1109	125.5	146.6	136.05	24.95	46.97	0.85	114.58

35	HP18	11	85	1600	175	57.75	0.25	3189	5654	2764	10255	600	273	90.9	100.1	95.5	16.09	18.81	0.54	86.59
36	HP19	12	85	1200	175	57.75	0.25	2050	7537	3038	10771	623	319	122.1	138.1	130.1	13.61	19.94	0.59	125.95
37	HP20	11	100	800	200	66	0.25	1169	8008	3478	11819	866	866	141.9	152.5	147.2	12.41	25.31	0.53	232.84
38	HP21	11	70	1200	175	57.75	0.25	2367	7963	3095	10517	821	254	120.2	129.2	124.7	17.37	21.6	0.66	95.08
39	HP22	11	100	1200	175	57.75	0.25	1981	7627	2663	9855	713	102	128.1	132.8	130.45	12.66	17.51	0.46	135.83
40	RP4	12	85	700	175	57.75	0.25	1414	6709	3192	10615	897	821	143.9	143.5	143.7	11.17	21.4	0.59	215.91
41	RP5	11	70	600	162.5	53.625	0.25	1561	6168	2992	9768	985	792	129.8	133.4	131.6	11.16	15.86	0.61	176.57
42	RP6	11	100	600	162.5	53.625	0.25	1096	6375	2960	9463	840	840	138.4	146.6	142.5	8.87	16.23	0.43	252.25
43	RP7	11	70	800	162.5	53.625	0.25	1864	7103	3177	10311	953	632	138.9	118.7	128.8	14.64	21.1	0.61	132.43
44	RP8	11	100	800	162.5	53.625	0.25	1408	5919	2904	9527	864	656	129.6	124.9	127.25	9.61	17.31	0.43	189.19
45	RP9	11	85	600	150	49.5	0.25	1400	5790	2880	9590	840	736	135.1	139.6	137.35	8.89	15.84	0.46	197.92
46	RP10	11	85	600	175	57.75	0.25	1136	7397	3346	10553	965	889	147.4	150.9	149.15	11.04	20.26	0.54	230.9
47	RP11	11	85	800	150	49.5	0.25	1808	5207	2600	9143	792	664	107.6	120.8	114.2	10.15	13.38	0.46	148.44
48	RP12	11	85	800	175	57.75	0.25	1494	6942	3173	10443	899	621	129.9	140.9	135.4	12.1	20.65	0.54	173.18
49	RP13	10	70	700	162.5	53.625	0.25	1616	6558	3056	9590	984	704	131.4	134.5	132.95	12.47	16.87	0.56	137.59
50	RP14	12	70	700	162.5	53.625	0.25	1776	6253	3372	10893	907	754	122.5	134.5	128.5	12.15	22.12	0.67	165.11
51	RP17	11	70	700	150	49.5	0.25	2080	5524	2893	9517	877	877	125.7	122.6	124.15	11.83	15.78	0.56	139.71
52	RP18	11	70	700	175	57.75	0.25	1887	5297	1958	9811	1272	1272	121.3	124.1	122.7	13.37	18.64	0.66	162.99
53	RP22	12	85	600	162.5	53.625	0.25	1145	7159	2153	9383	496	496	145.1	152.2	148.65	8.27	15.16	0.55	233.9
54	RP23	10	85	800	162.5	53.625	0.25	1617	6503	2088	8983	880	584	141.6	137.9	139.75	11.34	13.56	0.46	146.19
55	RP26	11	85	700	162.5	53.625	0.25	1310	5990	3051	9879	945	730	131.4	134.5	132.95	9.69	17.97	0.5	183.78
56	RP27	11	85	700	162.5	53.625	0.25	1565	5897	3051	10058	1017	942	130.4	142.2	136.3	10.46	18.56	0.5	183.78

Appendix B – Data presentation

Within this stage the use of standard Microsoft tools allowed the programming phase to be developed using a simple formatting systems within an Excel spreadsheet.



The results file imported into the Excel spreadsheet shows a snapshot of the level of numerical data required for the welding input parameters, identified within the column and the respective sample.

To correlate the bead geometries that corresponded with each sample a customised toolbar known as 'Format All' was created within Excel. All other tools described in **Table A-1** below.

Table A-1: Task of Customised Toolbar

	TOOL	DESCRIPTION
1	***FORMAT ALL***	This function is used to format the colour for the column. Blue, yellow, grey and white represents Sample, RUN ID, Welding Input Parameters and Weld bead geometries respectively. All text headers are formatted to"Calibri,20, bold"
2	***IMAGE***	This function import all the weld macrograph images to column 1.
3	***COMMENT UNIT*** ***COMMENT DESCRIPTION***	This adds "Unit" and "Description" comments to the text header.
4	***BEAD ANGLE AVERAGE*** ***HEAT INPUT*** ***POWER RATIO***	This function performs the following calculation: Bead Angle Average, Heat Input and Power Ratio.
5	***INSERT FILTER*** ***UPDATE***	This function performs a data query to the data.

C. Acoustic Sensor

Single Manufacturing Platform Environment (SIMPLE) - Stage 2

Acoustic Sensor

NI1032-REP-03

NUCLEAR AMRC
ADVANCED MANUFACTURING RESEARCH CENTRE

Project report

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Executive summary

- The objective of this work package is to develop an approach to use airborne arc sound to predict the presence of welding defects.
- The technical motivation of the acoustic sensor package is:
    - Arc sound contains rich information about the welding process, such as the behaviour of the arc column, the molten metal and the metal transfer mode.
    - Expert welding operators are able to use sound and vision to monitor and control the welding process.
    - It has been demonstrated that without acoustic feedback, the performance of the welding process will be significantly degraded.
- The advantages of the acoustic process monitoring approach are:
    - Easy realisation of the online process monitoring.
    - Low cost of the sensor specification.
    - Flexible installation of the microphones.
- Technical challenges
    - The development of the necessary noise removal techniques is still in its infancy.
    - Data required by the existing methods for training defect classifier is expensive and time-consuming to obtain.
    - The performance of existing methods highly depends on the data analysis knowledge of adaptors.
    - The robustness and transferability of the proposed techniques have not been verified.
- Development path
    - Literature review.
    - Development of ambient noise removal.
    - Development of signal characterization process.
    - Development of machine learning defect classifier.
- Potential industrial impact
    - The defect detection can be performed in real-time which could significantly reduce the processing time.
    - The cost of the hardware set-up is significantly low compared with that of either traditional techniques, e.g. Ultrasonic NDE, or advanced techniques, e.g. laser scanner, which can significantly reduce the manufacturing cost.
    - The welding process monitoring based on acoustic data is potentially transferable to any manufacturing process that generating sound.

Contents

1 Technical challenge and first principles

1.1 Objectives & Motivation

In arc welding processes, e.g. gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW), the sound is generated from sources like the arc, shielding gas and welding equipment. Manz (1) found that an electrical arc generates a sound when the energy level of the arc changes, i.e. for every pulse of electrical energy put into an arc, a pulse of sound is created. Therefore, the signature of the arc sound contains rich information about the welding process, e.g. the behaviour of the arc column, the molten metal and the metal transfer mode. It is commonly believed that specialised welding operators are able to use a combination of arc sound and vision to monitor and control the welding process. Tarn and Huisson demonstrated that without the acoustic feedback, the welding performance will be significantly degraded (2). Thus, the objective of the acoustic sensor package is to investigate using the airborne acoustic signal generated to monitor the welding process. It aims to detect the presence of welding imperfections from the arc sound and classify them according to industrial standards such as ISO 6520 with the help of machine learning techniques.

1.2 State-of-the-art techniques

In the academic research field, there are many studies regarding the use of arc sound to monitor the welding process. Arata et al. (3) are the pioneers of systematically investigating the effects of different welding methods and conditions on arc sound. Saini and Floyd (4) are among the first to explore the use of arc sound on the weld quality control based on various audio, time and frequency-domain features. These features have then been further exploited for monitoring specific welding process states, such as keyhole status detection (5) and process stability assessment (6). Other signal characteristics of the welding arc sound have also been explored for the purpose of welding process monitoring, such as wavelet transform coefficients via wavelet package analysis (7), energy-frequency distance plot obtained via Hilbert Huang transformation (8) and sample entropy (9).

Except when using conventional signal processing techniques for welding process monitoring, an increasing number of studies have been conducted to investigate employing advanced machine learning techniques to achieve a more automatic and robust process. Tam (10) has studied the implementation of an artificial neural network for mapping welding arc acoustic spectral characteristics to process parameters. Wang and Huissoon (11) have explored two machine learning classification algorithms, i.e. the artificial neural network and naïve Bayesian classifier, to classify the welding processes of different parameters. Similarly, the artificial neural network has also been employed by Huang and Kovacevic (12) and Lv et al. (13) to perform a regression analysis to predict the depth of weld penetration. In addition to the artificial neural network, other classic machine learning algorithms have been demonstrated to be useful in a series of recent studies. For example, Sumesh et al. (14) have proved that the random forest is able to classify the welding quality, Song et al. (15) have employed the hidden Markov model to process the sound signal to predict the penetration states, and Zhao et al. (16) have studied the Gaussian mixture model for the welding transfer mode identification.

2 Starting MRL/TRL level

The starting TRL was deemed as level 2, with progress made towards level 3.

The starting MRL was deemed as level 1.

The justification for these values is shown in Appendix 1.

3 Overview of technical challenge for the industry

3.1 Technical challenges

Considering the related techniques proposed in the existing literature, there are many technical challenges restricting their application in practical use. Firstly, most of the existing techniques have only been tested on some simplified welding processes, e.g. bead-on-plate welding. Secondly, almost all their corresponding validation tests are conducted in laboratory environments where the acoustic situation is often idealised. However, in industrial environments, there are many other operating machines that act as sources of noise. This noise can potentially contaminate the recorded arc sound data and, thus, affect their performance. Therefore, the robustness of these techniques is in doubt. Thirdly, the data required by the existing techniques for training the classification models are expensive and time-consuming to obtain. For example, to train a defect classifier, it is necessary to simulate all the possible welding defect situations, which is not practically realisable, and it is also very difficult for well-trained welding operators to induce spontaneous imperfections at known locations on purpose. Lastly, to obtain an optimal performance using the existing techniques, machine learning experts are required to manually tune the model training process, e.g. optimisation of signal characterisation progress and model hyper-parameters. These steps are often case-specific which means that they must be repeated each time the technique is deployed to a different process or application.

In addition to the drawbacks of the existing proposed techniques, there also exists some inherent limitations of this acoustic process monitoring approach. The first one is that the process sound must be assessable in order to allow this acoustic approach to work. This requires the sound of interest to be not only recordable but also isolated from the other recorded sound, e.g. the ambient noise and arc sound from other sources. Then, the target process behaviours/status to be detected must be sound distinguishable, e.g. the sound of the good and bad welding process must be different to detect the welding defect. To conclude, as long as adequate above-requirement-satisfied acoustic data, i.e. assessable and deter-object-sensitive, required by the machine learning classification methods can be obtained, the acoustic monitoring approach can provide a desirable performance.

3.2 Work conducted and the development path

3.2.1 Acoustic sensor specification

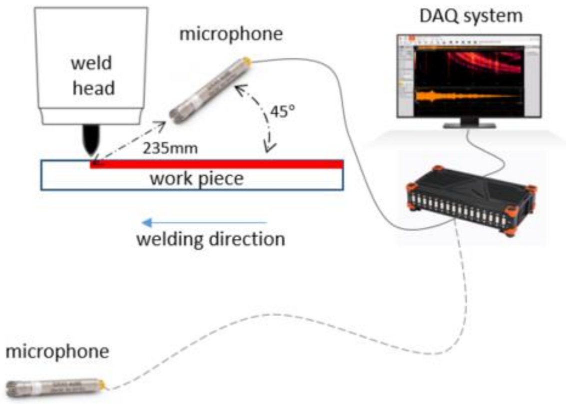

Figure 3-1 the schematic diagram of the sensor specification of the acoustic package.

The experimental setup used to perform the GTAW welding process and record the corresponding acoustic signal is schematically shown in Figure 3-1. *G.R.A.S. 46BE* microphones are used to measure the sound signal. As shown in Figure 3-1, two microphones are used. One of the microphones records the arc sound and is mounted on the welding head with a constant distance of about 235 mm from the welding torch and an approximated 75° angle from the work-piece. The other microphone is situated away from the welding head and records the ambient noise in the workshop environment. The data acquisition (DAQ) system used for collecting the sound data consists of a *Dewesoft SIRIUS* systems and *Dewesoft X3* data acquisition software.

3.2.2 Noise removal progress

The acoustic signals recorded from welding processes are often heavily corrupted by the ambient noise from other operating machines within and around the working environment. To achieve a good, defect prediction performance from the arc sound, it is crucial to perform appropriate signal processing techniques to increase the signal to noise ratio (SNR). In this work, the shop-floor noise has been classified into two types for different consideration, i.e. stationary and non-stationary components.

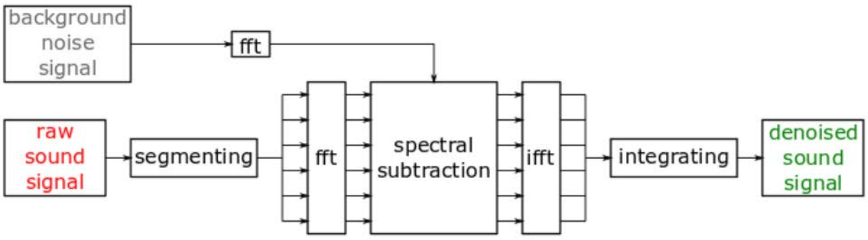

Figure 3-2 the schematic diagram of the application progress of spectral subtraction

Stationary noise (e.g. nearby continuously-operating machines, the flow of shielding gas), is reduced using spectral subtraction (17). This technique has already been proven effective in a similar application (12) and is a frequency-domain noise reduction method which subtracts the noise spectrum from that of the contaminated signal of interest. The noise spectrum is estimated from the sound signal recorded during the non-welding process. Figure 3-2 shows the schematic diagram of the application process of the spectral subtraction method which is described as:

1. Estimate the noise spectrum from the background sound signal via the fft (fast Fourier transform) process.
2. Segment the original time-series welding sound signal into a series of short-time-interval fragments.
3. Estimate the spectrum of each welding sound segment via the fft process.
4. Subtract the noise spectrum from that of each welding sound segment.
5. Estimate the time-series data of each de-noised sound spectrum via the ifft (inverse fast Fourier transform) process.
6. Reconstruct the de-noised welding sound signal via integrating the de-noised sound segments.

The non-stationary noise component caused by unpredictable operations, e.g. a crane passing overhead, often has a fixed frequency spectrum. Through this, the frequency spectrum can often be estimated in advance. Therefore, a band-stop filter is adopted to deal with the non-stationary noise.

Figure 3-3 shows an example result of the noise removal process on the arc sound signal. The first and second panels show the original contaminated signal and its corresponding de-noised signal after the noise removal process, respectively. It can be seen that the de-noise process adopted performs significantly well for noise reduction without sacrificing the information of the welding sound signal of interest.

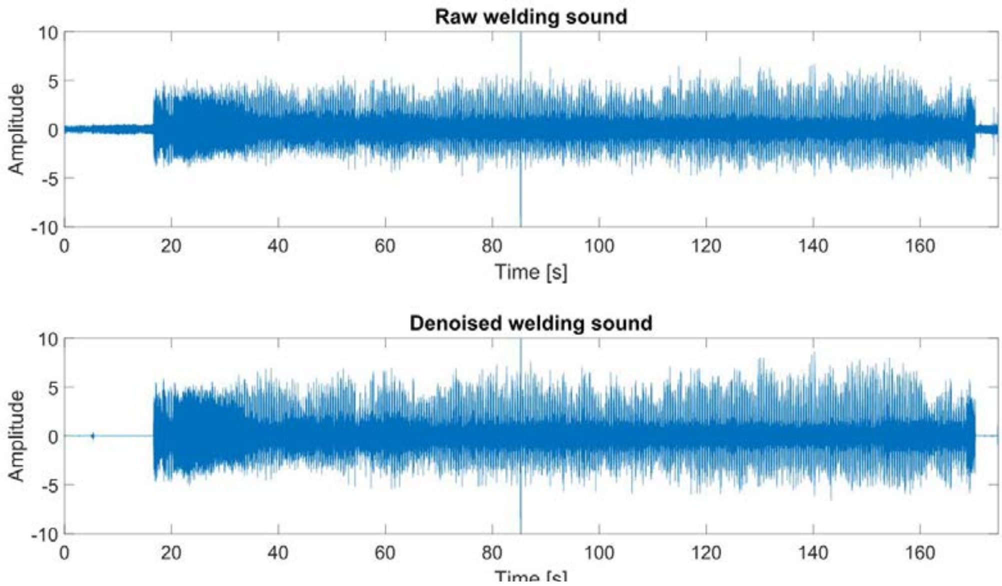

Figure 3-3 an example result of the noise removal progress

3.2.3 Signal characterisation progress development

In order to predict the welding quality from the acoustic signal, it is necessary to extract the correlated signal signatures. Here, we have considered the statistical features of the sound signal in both time and frequency domain.

In the time domain, twelve statistical features of the sound signal are considered and their definitions are listed in Table 3-1. It is intuitive to assume that the weldment quality could be related to the welding process intensity and stability. Thus, among the time-domain features under consideration, MA, SMR, RMS, AP, PP and ZCR qualify the power of the sound signal, while SF, CF, LF, IF, KV and SV are related to the sound uniformity and steadiness. In Table 3-1, $s(i)$ represents the i^{th} sampled point of the discretised time-series sound signal $s(t)$, i.e. $s(i) = s(i \cdot \Delta t)$ where $\Delta t = 1/f_s$ is the sampling time interval and f_s is the sample frequency, n is the number of data points in the sound signal and $\max(\,)$, $\min(\,)$ and $\mathrm{sgn}(\,)$ are the operators for extracting the maximum, minimum and sign of the considering terms respectively.

Table 3-1 the statistical features of the arc sound signal extracted in the time domain

Feature	Definition
Mean absolute amplitude (MA)	$\mu_{\lvert s \rvert} = \frac{1}{n}\sum_{i=1}^{n}\lvert s(i)\rvert$
Square mean root amplitude (SMR)	$\mu_{s_{smr}} = \left\{\frac{1}{n}\sum_{i=1}^{n}\sqrt{s(i)}\right\}^{2}$
Root mean square amplitude (RMS)	$\mu_{s_{rms}} = \left\{\frac{1}{n}\sum_{i=1}^{n}s(i)^{2}\right\}^{\frac{1}{2}}$
Absolute peak amplitude (AP)	$s_{max} = \max_{i\in[1,n]}(\lvert s(i)\rvert)$
Peak to peak amplitude (PP)	$s_{pp} = \max_{i\in[1,n]}\big(s(i)\big) - \min_{i\in[1,n]}\big(s(i)\big)$
Zero-crossing rate (ZCR)	$r_{zc} = \frac{f_s}{n}\sum_{i=2}^{n}\lvert \mathrm{sgn}\big(s(i)\big) - \mathrm{sgn}\big(s(i-1)\big)\rvert$
Shape factor (SF)	$\lambda_{sh} = \frac{\mu_{s_{rms}}}{\mu_{\lvert s \rvert}}$
Crest factor (CF)	$\lambda_{cr} = \frac{s_{max}}{\mu_{s_{rms}}}$
Clearance factor (LF)	$\lambda_{cl} = \frac{s_{max}}{\mu_{s_{smr}}}$
Impulse factor (IF)	$\lambda_{im} = \frac{s_{max}}{\mu_{\lvert s \rvert}}$
Kurtosis value (KV)	$\beta^{\frac{1}{4}} = \left\{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{s(i)}{\mu_{s_{rms}}}\right)^{4}\right\}^{\frac{1}{4}}$
Skewness value (SV)	$\gamma^{\frac{1}{3}} = \left\{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{s(i)}{\mu_{s_{rms}}}\right)^{3}\right\}^{\frac{1}{3}}$

In the frequency domain, the time-series sound signal, $s(t)$, is firstly processed using fast Fourier transformation to obtain its power spectral, $S(f)$. Here, the power spectral within the frequency range up to 20 kHz is considered. This frequency range is segmented into a population of fragments of 1 kHz bandwidth, where a 50% overlap is applied between each adjacent bandwidth fragments. For each bandwidth, eight statistical parameters are calculated as the candidate features, and their definitions are presented in Table 3-2. The first four parameters, i.e. PF, CF, RMSF and RVF, and the last three, i.e. AP, SDP and VP, describe the statistical distribution of the frequencies and power spectra of the sound signal within the corresponding bandwidth respectively. The parameter PC describes the power contribution of the considered bandwidth to the overall energy contained in the frequency range under consideration.

Table 3-2 the statistical features of the arc sound signal extracted in the frequency domain

Feature	Definition
Peak frequency (PF)	$f_p = \arg \max_{f_l \le f < f_u} (S(f))$
Central frequency (CF)	$f_c = \frac{\int_{f_l}^{f_u} f \cdot S(f)df}{\int_{f_l}^{f_u} S(f)df}$
Root mean square frequency (RMSF)	$f_r = \left[\frac{\int_{f_l}^{f_u} f^2 \cdot S(f)df}{\int_{f_l}^{f_u} S(f)df}\right]^{\frac{1}{2}}$
Root variance frequency (RVF)	$f_v = \left[\frac{\int_{f_l}^{f_u} (f - f_c)^2 \cdot S(f)df}{\int_{f_l}^{f_u} S(f)df}\right]^{\frac{1}{2}}$
Power contribution ratio (PC)	$r_s = \frac{\int_{f_l}^{f_u} S(f)df}{\int_0^{\infty} S(f)df}$
Average of power (AP)	$\mu_s = \frac{\int_{f_l}^{f_u} S(f)df}{f_u - f_l}$
Standard derivation of power (SDP)	$\sigma_s = \left[\frac{\int_{f_l}^{f_u} (S(f) - \mu_s)^2 df}{f_u - f_l}\right]^{\frac{1}{2}}$
Variation of power (VP)	$\lambda_s = \frac{\sigma_s}{\mu_s}$

3.2.4 Welding defect classifier development

Outlier detection, a non-supervised machine learning technique, was chosen to train the welding defect classifier. The main advantage of this technique is that only good welding data is required for classification model training, which means that the defect welding simulation is not necessary.

For a dataset, an outlier is defined as a data point that significantly differs from the remaining data (18). The appearance of an outlier is due to either system parameter errors during the data generation period, or a sensor fault during the collection process. Considering the defects as the outliers of a welding process, the problem may belong to the former. There are many algorithms developed to identify these outlying objects. These methods usually assume that there exists a 'normal' model of a dataset of interest, the outliers may be identified from the level of their deviation from the normal model, also known as outlier scores. Based on the approach for modelling the normal datasets, the outlier detection algorithms can be generally classified into the following categories: linear-model outlier detection (e.g. principal component analysis (PCA) (19)), proximity-based outlier detection (e.g. k-nearest neighbours (kNN) (20) (21)), probabilistic-model outlier detection (e.g. angle-based outlier detection (ABOD) (22)), outlier ensemble (e.g. isolation forest (IForest) (23)) and neural networks (e.g. *AutoEncoder* (24)). These outlier detection algorithms have been proven to be successful in many fields such as credit-card fraud analytics, network intrusion detection, medical diagnosis and mechanical system failure detection.

In this project, PCA is found to be a promising outlier detection technique to address the problem of welding defect prediction. Using singular value decomposition, PCA projects the original dataset into a new (maybe lower-dimensional) space of linearly uncorrelated variables (features), called the principal components. In this process, the covariance matrix of the dataset of interest is decomposed into orthogonal vectors, called eigenvectors, associated with eigenvalues. The eigenvalues represent the variance of the dataset projected in the direction of the corresponding eigenvectors. Considering the fact that the vast number of eigenvalues is relatively small in most real datasets, their variance could be mainly captured in a lower-dimensional subspace formed by the k largest eigenvectors. Thus, it can be assumed that the data point with a very large normalised distance from this k-dimensional hyperplane after projection is an outlier. However, here the first *k* eigenvectors are chosen in a hard way, while it is not an ideal approach for the outlier detection problem because *k* is an extra introduced hyper-parameter which there is no guidance of tuning in non-supervised settings. Alternatively, the weighted sum of the projected distance of a sample on all eigenvectors by the inverse of the corresponding eigenvectors is considered as the outlier score here and this approach is called *soft* PCA.

The detailed procedure of applying soft PCA for outlier detection can be described as the followings:

1. Determine the covariance matrix, $\boldsymbol{K}$, of the training dataset, $\boldsymbol{D}$, i.e.

$$\boldsymbol{K} = \frac{\boldsymbol{D}^{\mathrm{T}}\boldsymbol{D}}{N}. \tag{1}$$

2. Calculate the mean vector of the training dataset in each dimension, denoted as $\boldsymbol{\mu}$.
3. Calculate the outlier scores of all the instances in the training dataset, $\boldsymbol{X}_i$, i.e.

$$\mathrm{Score}(\boldsymbol{X}_i) = (\boldsymbol{X}_i - \boldsymbol{\mu}) \cdot \boldsymbol{K}^{-1} \cdot (\boldsymbol{X}_i - \boldsymbol{\mu})^{\mathrm{T}}. \tag{2}$$

4. Determine the threshold from the distribution of the outlier scores of the training data instances.
5. Calculate the outlier score of test data instances, $\boldsymbol{Y}_j$, i.e.

$$\mathrm{Score}(\boldsymbol{Y}_j) = (\boldsymbol{Y}_j - \boldsymbol{\mu}) \cdot \boldsymbol{K}^{-1} \cdot (\boldsymbol{Y}_j - \boldsymbol{\mu})^{\mathrm{T}}. \tag{3}$$

6. Classify the test instance as an anomaly if its outlier score is larger than the threshold.

Here *N* is the number of instances in the training dataset, d is the number of features, and ***D*** is a matrix of dimension $\{N \times d\}$ consisting of normal state data only.

In Figure 3-4 the prediction based on the time-domain features is shown. The y-axis represents the outlier score, and the x-axis represents the data point index. The black dots correspond to good welding data, whereas the colourful dots correspond to different cases of poor welding parameters. The dashed line represents the threshold. The data points with outlier scores larger than the threshold are regarded as outliers. It can be seen that the prediction is unsatisfied.

This is because the time-domain features considered are only related to the sound power and sound stability which may not be good enough for distinguishing the good and bad welding simulated in our project.

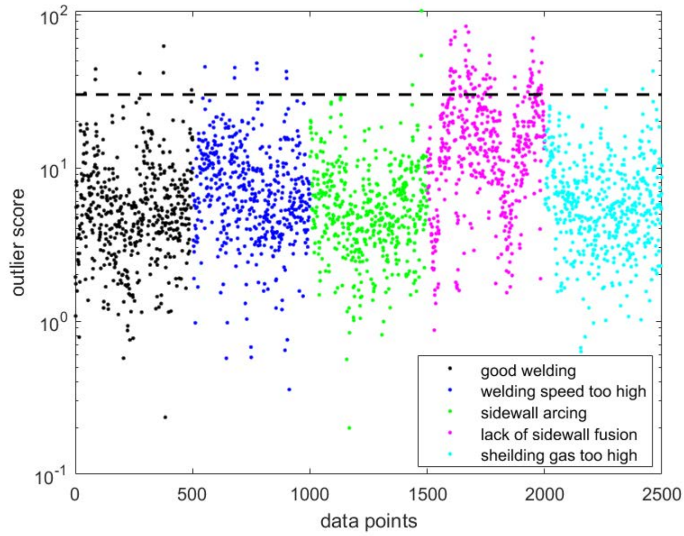

Figure 3-4 an example result of PCA outlier detection model based on time-domain features

In Figure 3-5, the prediction based on the frequency-domain features is shown. It can be seen that the model can accurately classify the different examples of poor welding parameters. This is shown by all the good welding data points falling below the threshold line, while all the poor parameter welding points appearing above it.

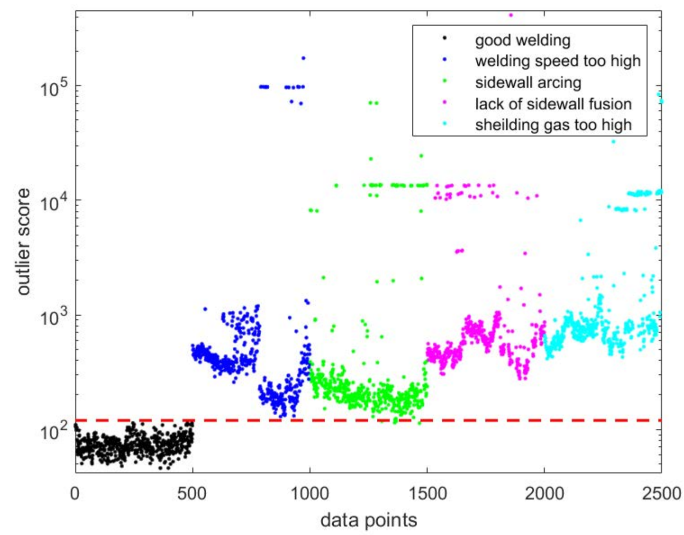

Figure 3-5 an example result of PCA outlier detection model based on frequency-domain features

Except for technical instructions described above, there are several other suggestions if someone else plans to build the system:

- Although there is no specific instruction about where to place the microphone for recording arc sound, it is suggested to ensure this microphone point to the welding pool as close as possible.

- Before any data processing, it will always be beneficial to visually and audibly examine whether the arc sound is correctly measured.
- Before applying any noise removal techniques, it is always worth trying to use the raw sound data to train classifiers and assess whether their performance could satisfy the requirement because any noise removal methods will filter the useful information in some degree.
- Although the bad welding sound data is not required to train the model, it is still suggested to simulate and obtain some of them for validating the trained classifier before the practical use.

4 Conclusions and Future work

4.1 End MRL/TRL level

The results of the work outlined above have demonstrated that most of the requirements of TRL3, with some progress made towards TRL 4, and MRL3. The justification for these values is shown in Appendix 1.

4.2 Potential industrial impact

There are several obvious benefits of using the acoustic signal to monitor the welding process. For example, it can easily realise the application of real-time manufacturing process monitoring, which can save a significant amount of inspection time and cost. Also, it can help to build confidence in the welding process and remove the need for unnecessary mid-process non-destructive evaluation (NDE). Compared to the other inspection approaches, e.g. ultrasonic NDE, the equipment cost of this technique and complexity of data acquisition is significantly lower. For example, the classification model training process can be conducted remotely or even in the cloud, which means that to deploy this approach, only several microphones and a compatible data acquisition system are required. Therefore, the acoustic monitoring system could also be developed and deployed within a small to medium-sized enterprise (SME). The sensor installation process is also very simple as the microphone can be easily mounted on almost any welding head. Finally, because of the machine learning methods used, the performance of this technique can evolve in its service lifespan. For example, with more and more data collected from everyday use, the accuracy of the machine learning model could be continuously improved.

4.3 Future work

In order to extend the scope of the acoustic sensor package and raise it to higher TRL/MRL levels, the following future work is required:

- Test the application scope of the acoustic process monitoring approach in the workshop environment, e.g. different welding processes and different process parameters.
- Build an industrial welding sound dataset via collaborating with the supply chain to acquire more welding sound

data of different noise working environments, different operators and welding/workpiece materials and geometries.

- Test and optimise the proposed acoustic monitoring approach on different industrial welding sound datasets.
- Seek more candidate machine learning algorithms and including the promising ones into the acoustic monitoring system so that the ensemble prediction improves the robustness of the technique.
- Construct a real-time acoustic signal processing and machine learning prediction system to realise the in-process welding monitoring.

4.4 The route to industrial adoption

Considering the low TRL/MRL level of the acoustic process monitoring approach, its route to industrial adoption may be case-specific, which can be generally described as:

- Seeking potential industrial partners who are interested in this acoustic process monitoring technique.
- Understanding the requirements of the industrial partners such as inspection cost reduction, automatic product quality control, welding operator training, etc.
- Specifically designing the outputs of the monitoring system based on the requirement of the industrial partners.

4.5 Engagement with industry/academia

During the project, the acoustic sensor package has strong links with other work packages within the SIMPLE project, which results in many collaborative research possibilities. For example, the in-process monitoring package from the Department of Physics and Astronomy, University of Sheffield are interested in integrating multi-sensor signals to eliminate the ambient noise issue of the acoustic process monitoring.

The work results of the acoustic sensor package have been presented in the 72nd IIW Annual Assembly and International Conference, Bratislava, Slovakia. During the conference, the welding inspection experts from Structural Integrity Technologies Inc. (SINTEC), Canada and Helmholtz-Zentrum Geesthacht, Germany, have provided much useful advice on the future work and potential application of the acoustic process monitoring approach, such as how to realise the in-process monitoring, how to use acoustic sound to feedback control the welding process, and how to deal with the situation where multiple arc sound sources exist in the same environments.

References

1. *Welding Arc Sounds.* **Manz, AF.** 5, 1981, Welding Journal, Vol. 60, pp. 23-27.

2. *Developing psycho-acoustic experiments in gas metal arc welding.* **Tarn, J. and Huissoon, Jan.** 2005. IEEE International Conference Mechatronics and Automation, 2005. Vol. 2, pp. 1112-1117.

3. *Investigation on welding arc sound (Report I): effect of welding method and welding condition of welding arc sound (welding physics, processes & instruments).* **Arata, Yoshiaki, et al.** s.l. : 大阪大学溶接工学研究所, 1979, Transactions of JWRI, Vol. 8, pp. 25-31.

4. *An investigation of gas metal arc welding sound signature for on-line quality control.* **Saini, D. and Floyd, S.** s.l. : AMERICAN WELDING SOC, 1998, WELDING JOURNAL-NEW YORK-, Vol. 77, pp. 172--s.

5. *Noncontact acoustic analysis monitoring of plasma arc welding.* **Wang, Yaowen and Zhao, Pensheng.** s.l. : Elsevier, 2001, International journal of pressure vessels and piping, Vol. 78, pp. 43-47.

6. *Feasibility study of acoustic signals for on-line monitoring in short circuit gas metal arc welding.* **Grad, Ladislav, et al.** s.l. : Elsevier, 2004, International Journal of Machine Tools and Manufacture, Vol. 44, pp. 555-561.

7. *Wavelet Package for the In-Process Monitoring of Gas Metal Arc Welding Mild Steel.* **Ting, Ying Yao, Hung, King Chu and Tzeng, Yih Fong.** 2012. Applied Mechanics and Materials. Vol. 121, pp. 3652-3656.

8. *Porosity detection by analyzing arc sound signal acquired during the welding process of gas pipeline steel.* **Yusof, M. F. M., et al.** s.l. : Springer, 2017, The International Journal of Advanced Manufacturing Technology, Vol. 89, pp. 3661-3670.

9. *Quantitative evaluation method of arc sound spectrum based on sample entropy.* **Yao, Ping, Zhou, Kang and Zhu, Qiang.** s.l. : Elsevier, 2017, Mechanical Systems and Signal Processing, Vol. 92, pp. 379-390.

10. **Tam, Joseph.** *Methods of characterizing gas-metal arc welding acoustics for process automation.* University of Waterloo. 2005. Master's thesis.

11. *Classifying Arc Acoustic Data in GMA Welding Using Artificial Neural Network and Naïve Bayesian Classifiers.* **Wang, James J. and Huissoon, Jan P.** 2009. Proceedings of the 8th International Conference on Trends in Welding Research. pp. 461-66.

12. *A neural network and multiple regression method for the characterization of the depth of weld penetration in laser welding based on acoustic signatures.* **Huang, Wei and Kovacevic, Radovan.** s.l. : Springer, 2011, Journal of Intelligent Manufacturing, Vol. 22, pp. 131-143.

13. *Real-time control of welding penetration during robotic GTAW dynamical process by audio sensing of arc length.* **Lv, Na, et al.** s.l. : Springer, 2014, The International Journal of Advanced Manufacturing Technology, Vol. 74, pp. 235-249.

14. *Use of machine learning algorithms for weld quality monitoring using acoustic signature.* **Sumesh, A., et al.** s.l. : Elsevier, 2015, Procedia Computer Science, Vol. 50, pp. 316-322.

15. *Penetration state recognition based on the double-sound-sources characteristic of VPPAW and hidden Markov Model.* **Song, Shuo, et al.** s.l. : Elsevier, 2016, Journal of Materials Processing Technology, Vol. 234, pp. 33-44.

16. *GMAW metal transfer mode identification from welding sound.* **Zhao, Sipei, et al.** 2018, Proceedings of ACOUSTICS 2018.

17. *Suppression of acoustic noise in speech using spectral subtraction.* **Boll, Steven.** s.l. : IEEE, 1979, IEEE Transactions on acoustics, speech, and signal processing, Vol. 27, pp. 113-120.

18. **Aggarwal, Charu C.** *Outlier Analysis.* 2nd. s.l. : Springer International Publishing, 2017.

19. **Shyu, Mei-Ling, et al.** *A novel anomaly detection scheme based on principal component classifier.* MIAMI UNIV CORAL GABLES FL DEPT OF ELECTRICAL AND COMPUTER ENGINEERING. 2003. Tech. rep.

20. *Efficient algorithms for mining outliers from large data sets.* **Ramaswamy, Sridhar, Rastogi, Rajeev and Shim, Kyuseok.** 2000. ACM Sigmod Record. Vol. 29, pp. 427-438.

21. *Fast outlier detection in high dimensional spaces.* **Angiulli, Fabrizio and Pizzuti, Clara.** 2002. European Conference on Principles of Data Mining and Knowledge Discovery. pp. 15-27.

22. *Angle-based outlier detection in high-dimensional data.* **Kriegel, Hans-Peter, Zimek, Arthur and others.** 2008. Proceedings of the 14th ACM SIGKDD international conference on Knowledge discovery and data mining. pp. 444-452.

23. *Isolation forest.* **Liu, Fei Tony, Ting, Kai Ming and Zhou, Zhi-Hua.** 2008. 2008 Eighth IEEE International Conference on Data Mining. pp. 413-422.

24. *Outlier detection with autoencoder ensembles.* **Chen, Jinghui, et al.** 2017. Proceedings of the 2017 SIAM International Conference on Data Mining. pp. 90-98.

D.Ultrasonic Sensor

Centre for Ultrasonic Engineering

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University of Strathclyde Engineering

SIMPLE - '**Si**ngle **M**anufacturing **Pl**atform **E**nvironment' project to develop a single platform for the manufacture of nuclear components

Final report on the feasibility of using an Ultrasonic inspection system in the proposed SIMPLE environment

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Revision	**Date of issue**	**Reason for revision or original issue**
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Contents

1 Executive Summary

- Ultrasound inspection is a well-recognised technique, with international standards, for inspecting completed welds. In-process inspection of multi-pass welds has to address a number of additional challenges, including:
    - Finding approaches that tolerate the extremes of temperature;
    - Correcting for the defocusing and beam bending associated with elevated temperatures and their gradients;
    - Identifying a mechanism to avoid false reporting of Lack of Fusion (LOF) defects from unfinished parts of the weld.

- There is much current research on high temperature array assemblies suitable for weld inspection, both at the University of Strathclyde and elsewhere, but these are all still at low TRL levels and so not available in the SIMPLE project timescales. As a result, the emphasis has been on adopting current commercial state-of-the-art devices into approaches that can address the above challenges.

- The aim was to investigate In-Process Ultrasonic Inspection to provide early defect detection, saving costs by:
    - Providing early process control feedback, leading to defect-free manufacture;
    - Avoiding moving the part to a separate inspection facility (& back for re-work);
    - Automating the inspection process, which also improves consistency of detection.

- In all cases, the results were compared with the inspection of the completed weld

- The investigations confirm the feasibility of the approach and result in a recommended system.

2 Technical Challenges and first principles

2.1 Background

Ultrasound inspection is a well-established Non-Destructive Evaluation (NDE) technique for ensuring the integrity of welds, with appropriate international standards (1), (2), (3) covering equipment, techniques and calibration. The usual approach involves inspection of the completed weld, after a minimum defined period to allow for the stabilisation of the material, from various angles and from a range of positions. Some defects, such as lack of fusion, produce specular reflections, and the standards lay down rules for the minimum number of inspection angles and locations that ensure these defects are always detected.

In the past, this has meant a variety of probes mounted on acoustic wedges to generate the necessary inspection angles. These assemblies are mechanically translated in two dimensions on the material surface to ensure the full volume is covered. Acoustic couplant gels are used between the transducer and the wedge, and between the wedge and the inspection surface, to remove any air gaps that would prevent the passage of the ultrasound.

Current practice uses an ultrasonic array on an acoustic wedge, again with couplant gel to ensure propagation of the ultrasound beams. Electronic steering and scanning generates the range of inspection beam profiles through the weld cross-section, requiring only mechanical translation in one dimension along the weld to achieve the same volumetric coverage.

A key aim of the SIMPLE project is to provide detection of any defects as each layer is added, as a way to provide early welding process control feedback, and also to allow for immediate rectification of any defects before the next layer is added.

3 Overview of the technical challenge for industry

There are a number of issues to be addressed when adapting these proven ultrasound inspection techniques for the new approach of inspection during welding. These include:

3.1 Hydrogen cracking

Inspection whilst welding means, by definition, that the material stabilisation during the extended cooling period will not have taken place. As a result, any defects that appear during this stabilisation process, such as hydrogen cracking, will not be detected. Until there is further investigation on whether these types of defects can be inferred from detectable properties at weld time, they will remain to be detected on the final, cold inspection after material stabilisation.

3.2 Tolerance of sensor to elevated temperature

The ultrasound array sensor head will now be in contact with hot material, typically much hotter than can be tolerated by standard components, so alternative approaches need to be considered. The same is true of the ultrasound couplant. High temperature ultrasound inspection has been the subject of research for many years, but techniques at extreme temperatures are still at low TRL levels and so are not appropriate for the SIMPLE timescale. Some approaches at intermediate temperatures, up to 150°C, are available commercially and these, along with their operational constraints, will be the focus.

3.3 Noise and interference

The ultrasound data-collection hardware operates at the limits of the electronic thermal noise. Whilst this noise level is likely to be increased by the higher temperatures around a robotic welding rig, it is far more likely that the electronic interference from the welder and the robot manipulators will determine the effective limit on sensitivity.

3.4 Beam bending due to temperature gradients

The speed of sound, both in the acoustic wedge and within the weld and parent material, is affected by temperature and so the timing controls used for electronic scanning need to factor in the changed temperature to keep the beams at the desired angles and focus. More of a problem is that any temperature gradients will result in the ultrasound beams bending, giving rise to errors in location of any defects.

3.5 Suppression of false positive indications

All the NDE inspection standards assume a completed weld. However, this is not the case for all but the last weld pass when inspecting whilst welding. The beam positions and orientations in the weld standards are defined to guarantee the detection of specular reflections from Lack of Fusion (LOF) defects. Here an echo in an appropriate location that exceeds a specified amplitude threshold is used to indicate the presence of such a defect. Until the last pass, there will be very strong specular reflections in these locations from the flat surfaces above the current weld pass. These expected indications will need to be suppressed, whilst still flagging any such echoes from within the part of the weld that has been filled.

3.6 Applicability of TIG Robot Cell to SIMPLE weld geometry

The SIMPLE platform uses narrow groove Gas Tungsten Arc Welding (GTAW), though the ultrasound inspection techniques should be equally applicable to other weld configurations. The ultrasonic inspection standards for the final weld are similar for either configuration, with the main differences being the use of tandem pitch-catch beam paths for narrow groove welding compared to direct or backwall-reflected pulse-echo paths for single-V butt welds, to detect specular reflections. The TIG (Tungsten Inert Gas) welding robot cell at University of Strathclyde is currently unable to do narrow-groove welding. However, the issues outlined above, such as sensors that can tolerate the raised temperatures and imaging that can work with temperature gradients, are similar for both and so using V-gap welding is still a valid approach for this phase.

4 Starting MRL/TRL level

Ultrasonic inspection of the completed weld using phased arrays is standard industry practice supported by international standards, and so is at a high TRL level. Extending this to the high surface temperatures in the SIMPLE environment, or where there are likely to be significant temperature gradients is at a much lower TRL level. Combining this, with the autonomous robotic deployment of the ultrasonic array in conjunction with the welding robot, means that the starting TRL level is 2. The equivalent MRL level at the beginning of the investigation is 1. The justification for these values is shown in Appendix 1.

5 Technical Challenges and how they were addressed

5.1 Creating Staircase reference specimen for evaluating part-fill images

NDE standards require the inspection equipment to be setup on calibration blocks, the acceptance levels set as a threshold, and any echo exceeding the threshold to be flagged as a potential indication. The material used for the calibration block will be the same as (or as close as practicable to) the material to be inspected. For inspection at elevated temperatures, the ideal is to have the calibration block at the same temperature, otherwise appropriate compensation (such as a change to the acoustic velocity) will be needed.

In addition to the calibration block, it is common practice for there to be a reference specimen as close as possible to the inspection geometry and containing features that should be detected. Typically, both the calibration block and the reference specimen would be inspected before and after the shift to confirm the validity of any inspection results that occurred during the shift.

As previously indicated, inspection whilst welding will require the amplitude threshold to be constrained to within a region of interest, which progressively expands as the weld passes are laid down. A "staircase" test block, where the full range of weld cross section profiles (containing all stages from none to fully welded) is available in the same block, is therefore an ideal reference specimen.

5.1.1 Specification of Staircase specimen

The material properties and the profile geometry of the pre-welded Staircase reference specimen are detailed in Table 5-1 and the properties of each weld pass are given in Table 5-2.

Table 5-1 Material properties and pre-welded geometry

Property	Value
Material	Steel (S275)
Material length	300mm
Material thickness	15mm
Weld profile	90deg V
Root face	1.5mm
Root gap	2.1mm

Table 5-2 Staircase reference specimen weld pass definition

Pass	Length	Pass Sequence	Thickness
Step 1 (Root pass)	270mm (0 to 270mm)	1	3.2mm (to 3.2mm)
Step 2 (Hot Pass)	230mm (0 to 230mm)	2	1.5mm (to 4.7mm)
Step 3	190mm (5 to 195mm)	3, 4	2.44mm (to 7.14mm)
Step 4	152mm (8 to 160mm)	5, 7, 6	2.26mm (to 9.4mm)
Step 5	117mm (8 to 125mm)	8, 10, 11, 9	3.46mm (to 12.86mm)
Step 6	80mm (10 to 90mm)	13, 15, 16, 14, 12	2.14mm (to 15mm)
Step 7 (Cap)	45mm (10 to 55mm)	19, 20, 21, 18, 17	Up to 4.3mm (to 19.3mm)

Figure 5-1 details the cross section geometry of the weld passes. Figure 5-2 is a photograph of the top surface of the completed Staircase reference specimen, with the array on high temperature wedge aligned with the mark to show the inspection position.

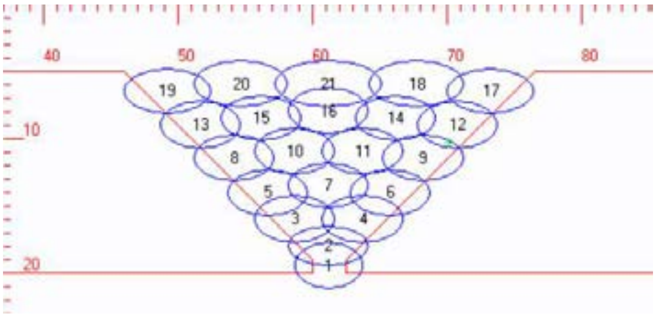


Figure 5-1 Cross section geometry of weld passes for Staircase reference specimen

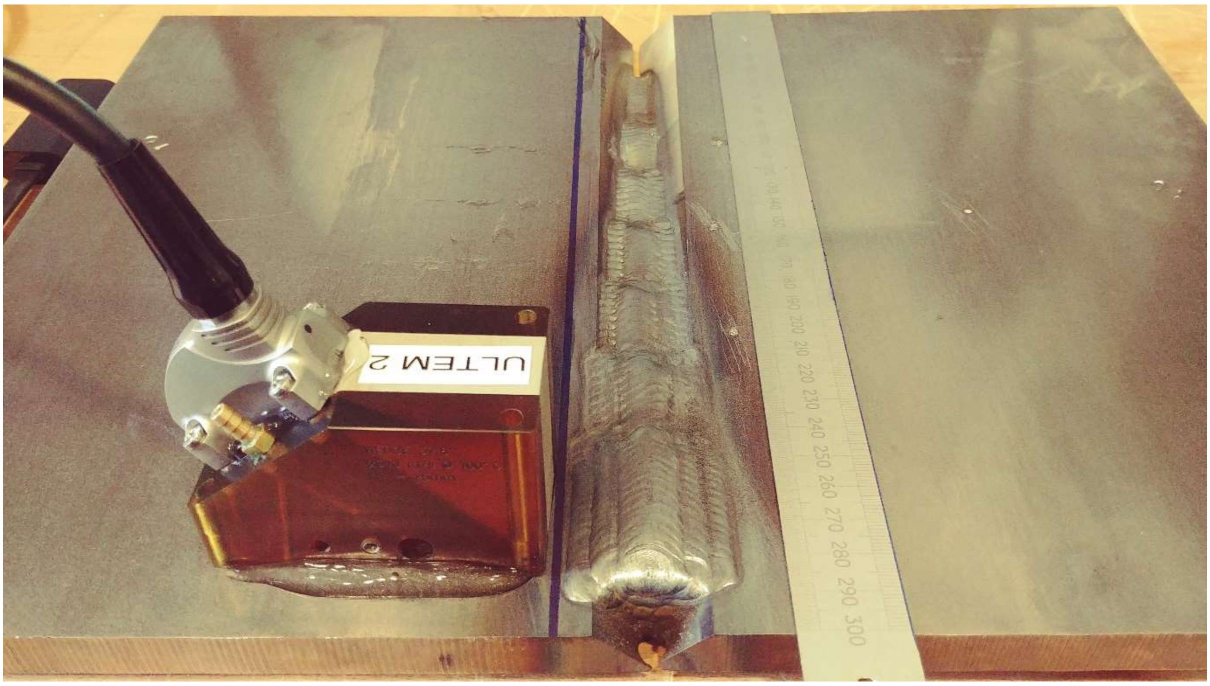
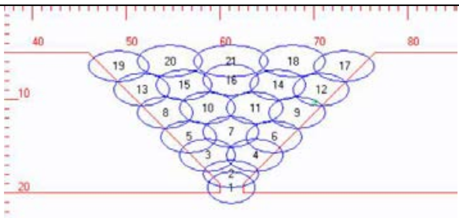
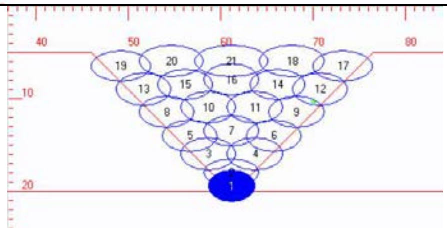
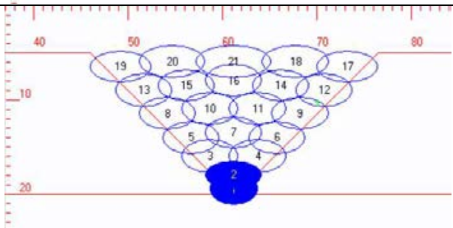
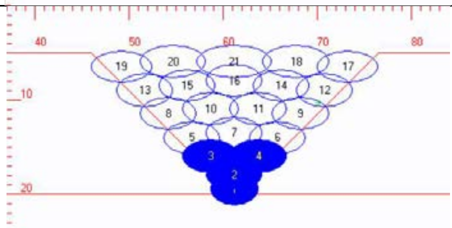
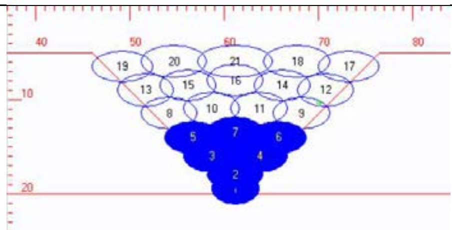
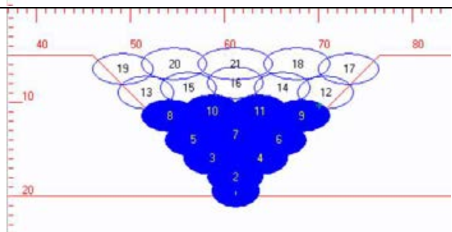
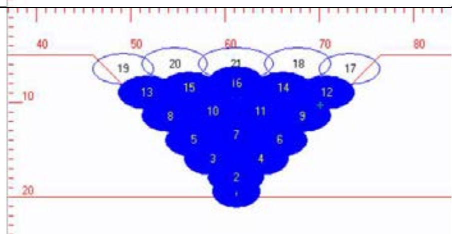
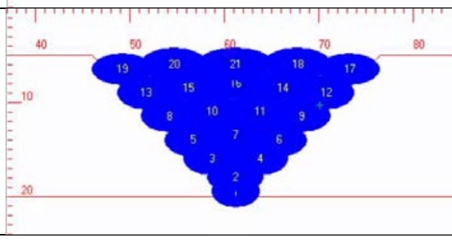


Figure 5-2 Top view of completed staircase test block with alignment mark for wedge positioning

Table 5-3 shows the weld cross section geometry for each step of the Staircase reference specimen, showing the weld passes for each case.

Table 5-3 Weld cross section for each step of the Staircase reference specimen

Step 0	
Step 1	
Step 2	
Step 3	
Step 4	
Step 5	
Step 6	
Step 7	

5.1.2 Results on Staircase reference specimen

The equipment used for the inspections of the Staircase reference specimen is listed in Table 5-4.

Table 5-4 Equipment used to inspect Staircase reference specimen

Equipment	Serial No.	Comments
Peak NDT LTPA Phased Array controller	18015	64 channel transmit / 64 channel receive / 64 element. Data collected using Peak NDT's "ArrayGen" software and Peak NDT's LabVIEW version.
Olympus 5MHz Array 5L64-32X10-A32-P-2.5-HY	T3728	5MHz 64 element phased array with 0.5mm element pitch.
Olympus High Temperature Acoustic Wedge SA32C-ULT-N55S-IHC		55° acoustic wedge fabricated from ULTEM high temperature acrylic with wedge angle of 37.6 ° and acoustic velocity at room temperature of 2470m/s and 2340m/s at 100°C.
Olympus High Temp Couplant H-2 (Q7700002)		-23°C to 398°C

The different regions of the weld are inspected using beam angles matched to the typical defects. For example, multiple reflections (skips) off the top and bottom faces are required for small-angled beams to reach the bevelled surface, whilst the root can be interrogated with a direct high-angle beam. The ray paths, shown in Table 5-5, illustrate this combination of angle and number of skips needed to inspect each colour-coded region of the weld.

Table 5-5 Ray paths, for varying number of beam skips, used to inspect different regions (colour-code) of the weld cross section

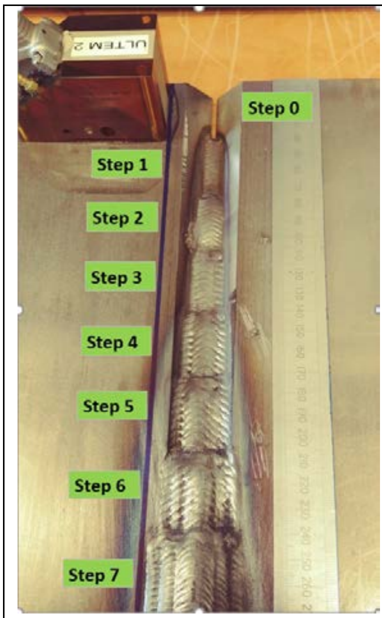
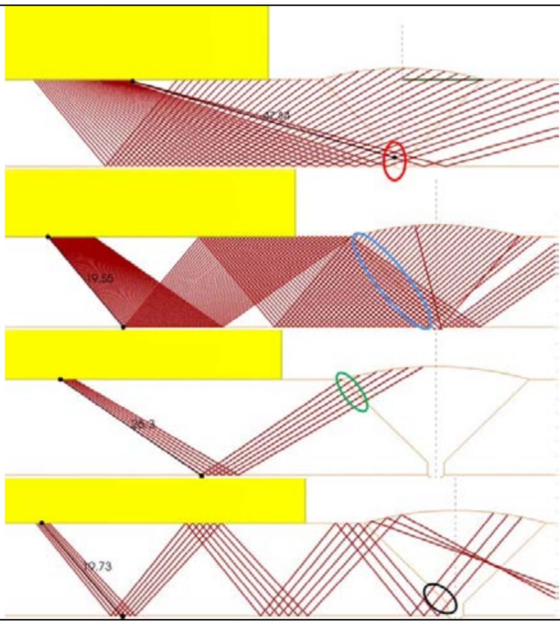
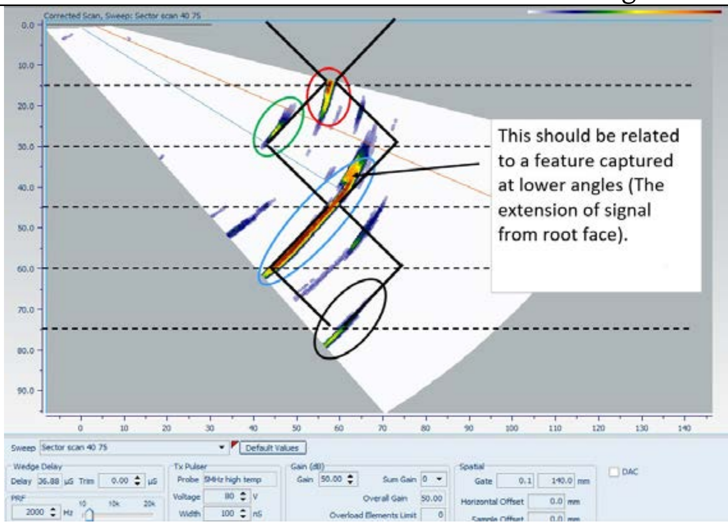
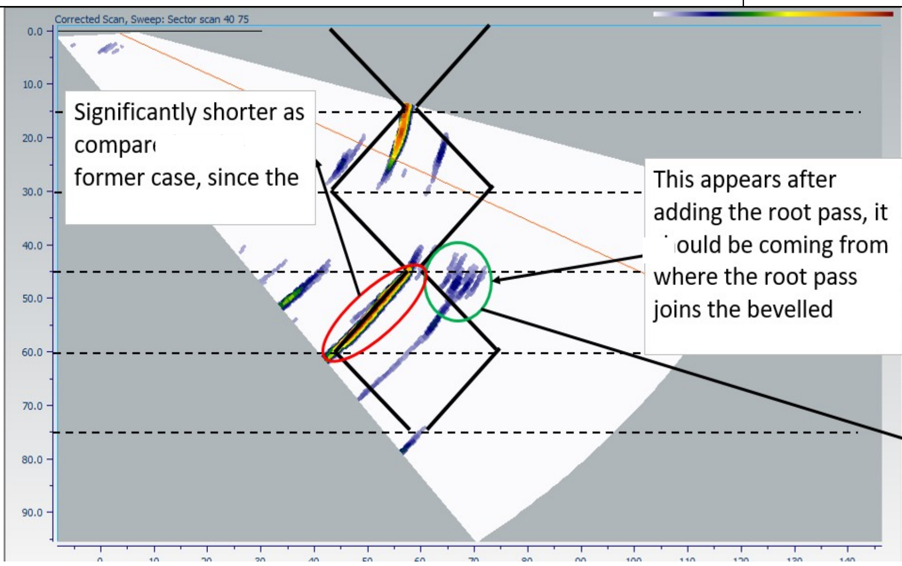
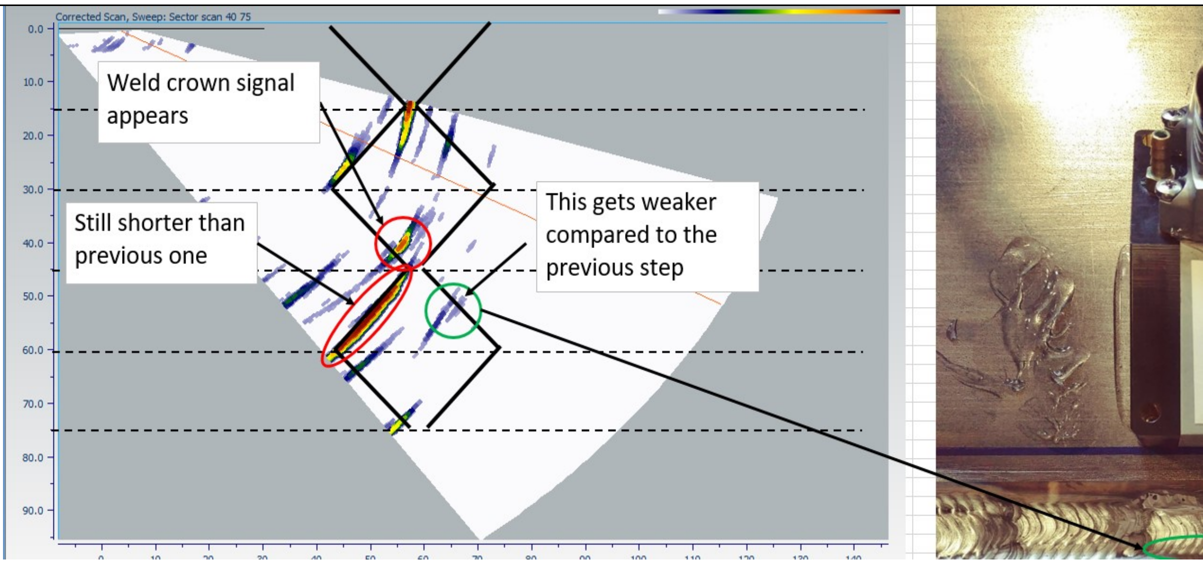
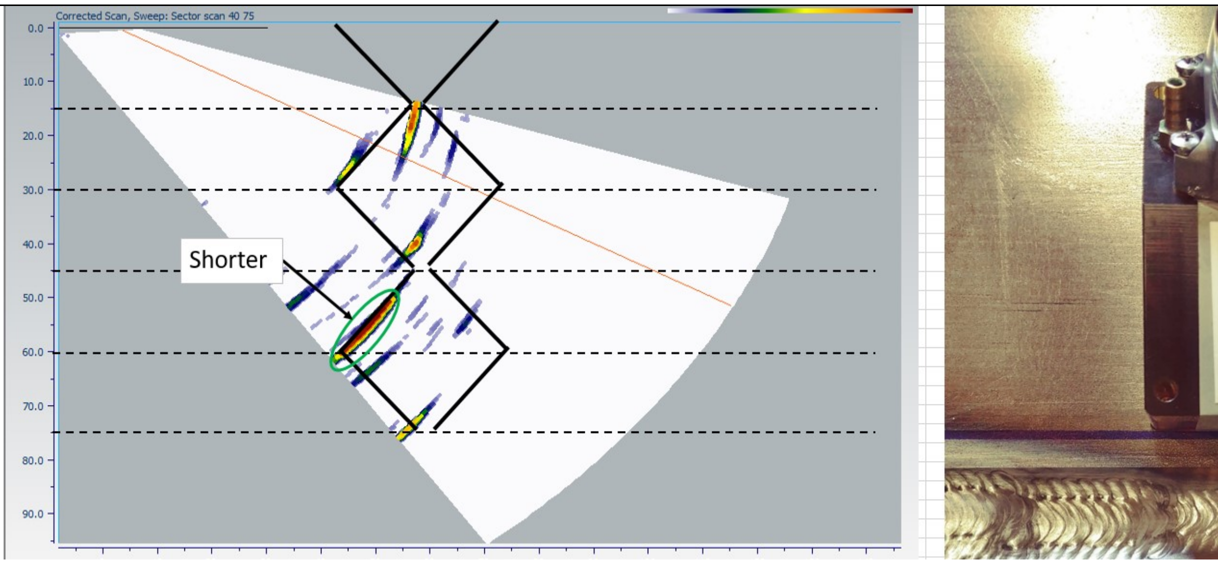
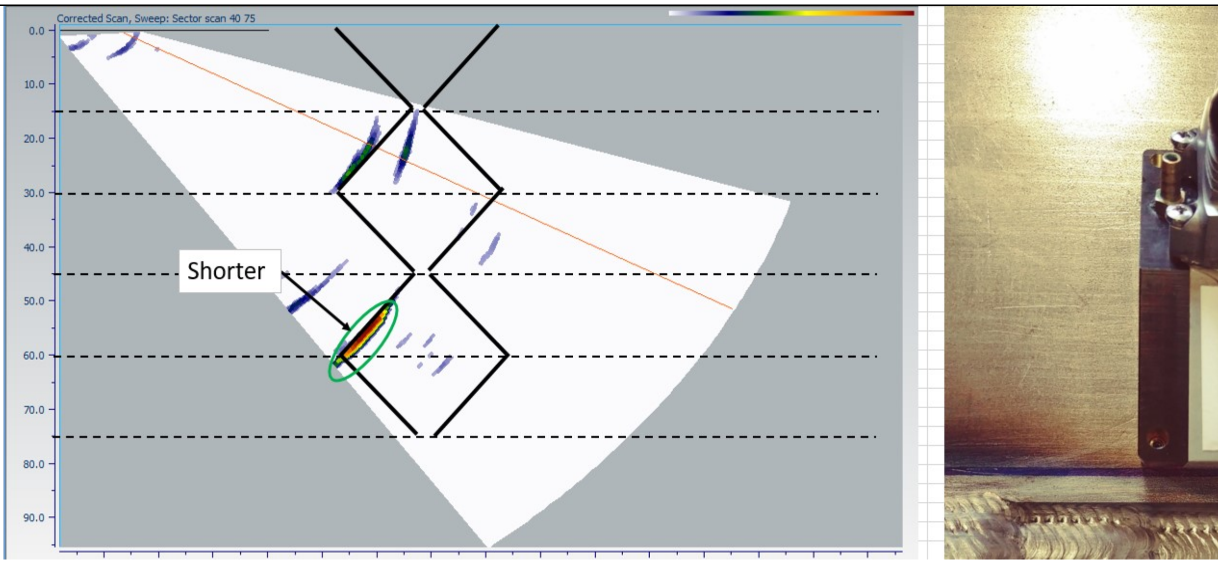
		1-Red circle shows an indication captured by high angle beam incident to the face root 2-Reflection of the top of bevelled surface captured by second half skip 3-Beveled surface captured by a range of low angle beams mixed with a reflection from the root face. Second skip 4- Root face reflection

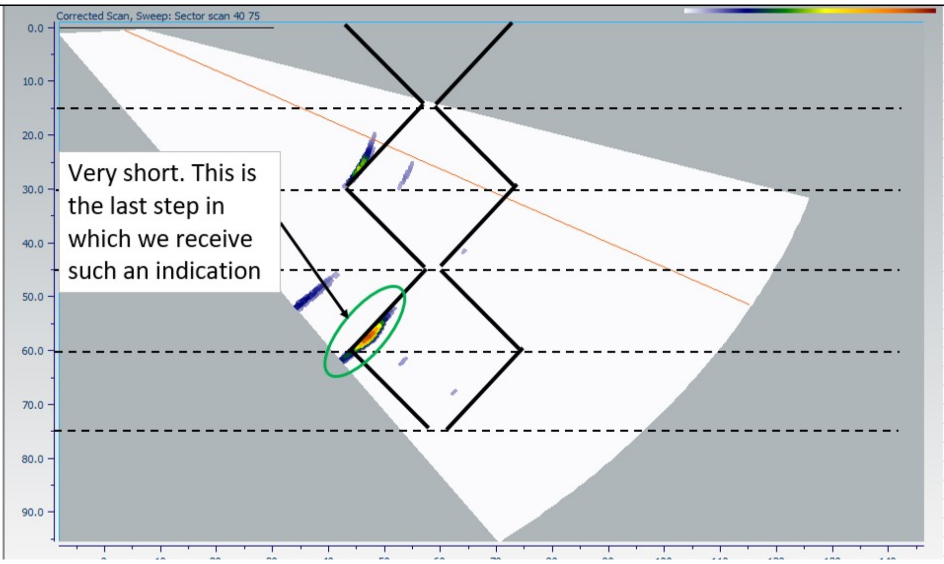
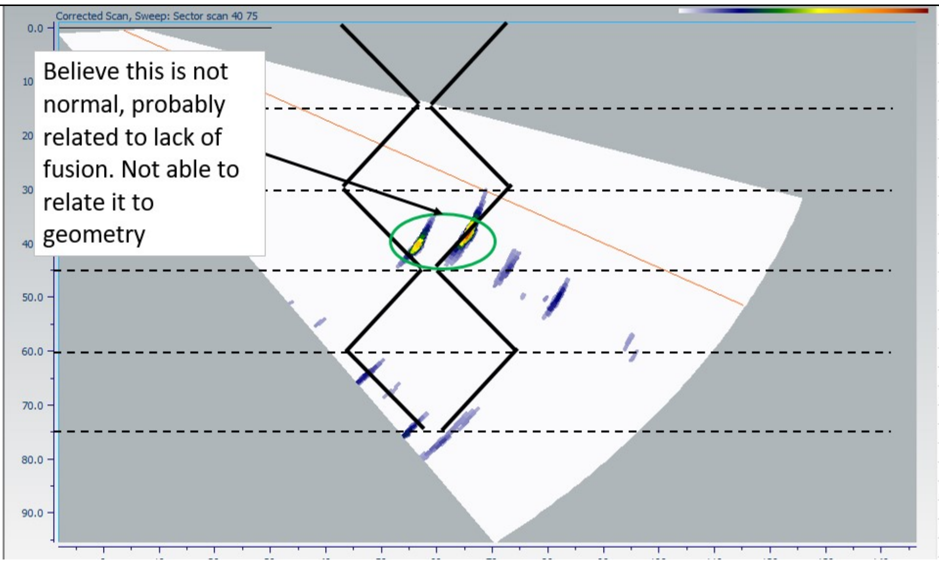
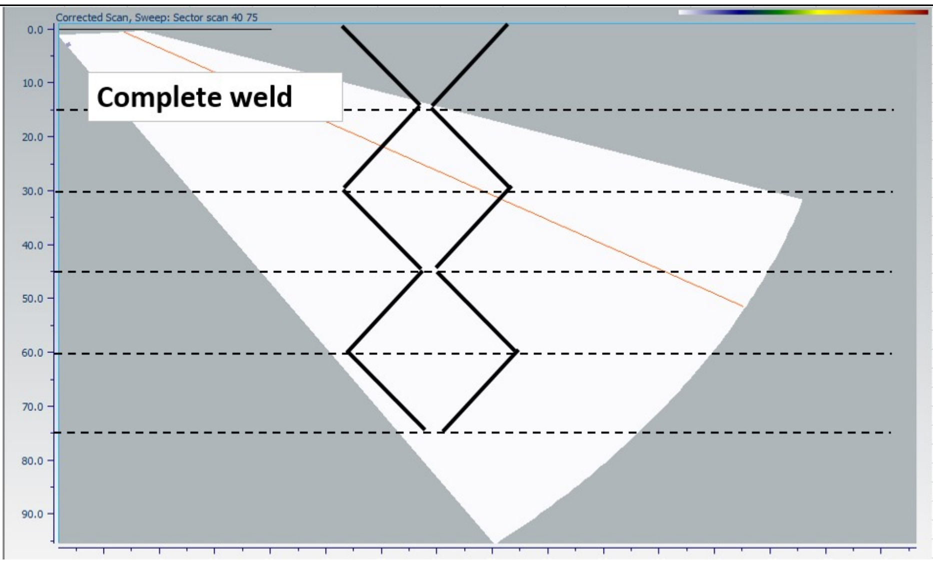
Table 5-6 shows the cross section images (B-scans) for each of the Staircase steps, using sector scan angles from 40° to 75° in 0.5° steps. Each image has an overlay of the top and bottom surfaces (dotted lines) and of the bevelled edges (solid oblique lines) to allow for better identification of the echoes. It also shows their repeat reflection positions from multiple skips.

The B-scan image for the completed weld (Step 7) is clean, confirming a defect-free build, and this is the expected result for the current procedure where only the completed weld is inspected. The echoes seen in the earlier steps are from the incomplete weld surfaces, and would be reported as Lack of Fusion defects were these same inspection procedures to be applied to incomplete welds. These echoes are therefore false-positives for the early stages of in-process inspection, and have to be masked. The change from a very large number of indications from the early steps, to a few in the later stages, indicates that this masking will need to change as the weld is filled.

Table 5-6 Cross sectional images from each step of the Staircase reference specimen showing the change as the weld is filled

Step	Image	
0		Reference image of the un-welded region (Step 0), showing the reflections from the bevel and root. The weld profile is shown at the top of the image and, with the array as close to the weld as possible, there are no direct beams to the weld. The top dotted line shows the position of the back wall, and the next marks the position of the reflection of the top surface. Subsequent dotted and oblique lines represent the top & bottom surfaces and the bevelled profile after subsequent reflections (skips).
1		

2	Corrected Scan, Sweep: Sector scan 40 75 Weld crown signal appears Still shorter than previous one This gets weaker compared to the previous step
3	Corrected Scan, Sweep: Sector scan 40 75 Shorter
4	Corrected Scan, Sweep: Sector scan 40 75 Shorter

5	Corrected Scan, Sweep: Sector scan 40 75 Very short. This is the last step in which we receive such an indication	
6	Corrected Scan, Sweep: Sector scan 40 75 Believe this is not normal, probably related to lack of fusion. Not able to relate it to geometry	
7	Corrected Scan, Sweep: Sector scan 40 75 Complete weld	

5.2 Evaluating potential image distortion at elevated temperatures

Even though the high temperature wedge protects the array from the degradations that occur above its maximum operating temperature of 60°C, there will be distortion in the image due to:

- Reduction in the acoustic velocity in the wedge due to the increase in temperature because of contact with the inspection surface. If the whole wedge was at the same elevated temperature, this would produce an increase to the apparent range to the echo due to the increased transit time in the wedge. It would also result in a geometrical distortion by means of the increase in the refracted beam angle due to the change in refractive index at the interface. If the temperature is uniform, it is simple to measure, and an appropriate compensation can be implemented to correct the geometry.
- The wedge material is chosen to provide a thermal barrier to protect the array, so the low thermal conductivity will give rise to large temperature gradients in the wedge, and these will bend the beams within the wedge.
- Both of the above will change with time, starting from the point where the array wedge first makes contact with the inspection surface. The low thermal conductivity means the temperature gradient is likely to be constrained to a relatively narrow strip along the inspection interface.
- Reduction in the acoustic velocity in the material due to the increase in temperature from welding (and any pre-heating). If the whole of the acoustic path from wedge to weld is at the same elevated temperature, this would produce an increase in the apparent range to the echo due to the different transit time in the material. It would also result in a geometrical distortion by means of the reduction in the refracted beam angle due to the change in refractive index at the interface. As with a uniform temperature in the wedge, a uniform temperature in the material can be measured and appropriate geometrical compensations implemented.
- If the inspection is performed soon after the weld pass, there will be large temperature gradients in the material and these will bend the beams within the material.

At NDT2018 (10-12 Sep 2018, Nottingham), TWI presented the results of ultrasound beam modelling simulations, using the CIVA modelling package from EXTENDE in France, of the effects of temperature gradients across the weld on the echo amplitude and location. In personal discussions after the paper, they confirmed that they are not publishing a written paper due to the confidential nature of the application. They also emphasised that the imaging was only being used for process monitoring rather than defect detection. The presentation indicated that whilst the echo amplitude change was around -1 or -2dB, the main effect was a positional change of up to 5mm. This geometrical shift is more than enough to affect the positioning of the Region of Interest (ROI) to mask the false-positives from the interfaces yet to be welded.

Our view is that the presence of the echoes, from the interfaces yet to be welded, can be used to provide a reference point to correct for most of the geometrical distortion. The position of the ROI mask can be shifted so that it aligns with the distorted position of these reference echoes, and the location of real defects within the welded part can be made relative to the interface.

5.2.1 Modelling of temperature gradients

To verify this, some Finite Element Analysis (FEA) simulations were performed using PZflex to replicate the CIVA modelling performed by TWI. Potentially it can be extended to look at temperature gradients within the wedge. Figure 5-1 (left) shows the geometry of the array+wedge to inspect the weld and (right) showing the thermal zones resulting from the FEA simulation.

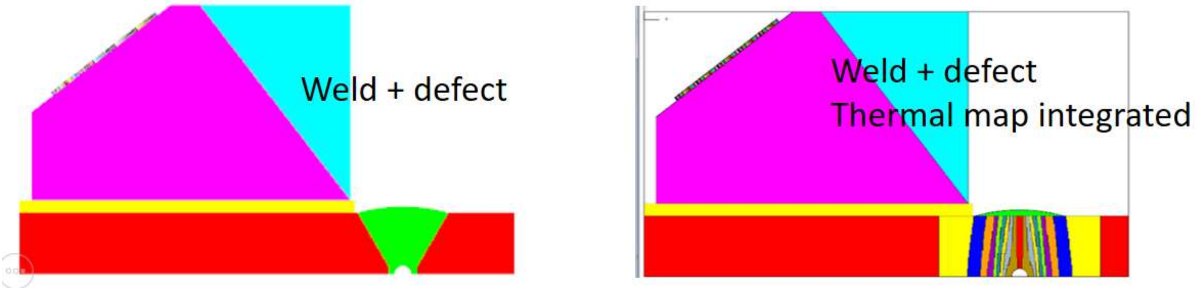


Figure 5-3 Cross section of weld with wedge (left) and showing thermal zones (right) resulting from FEA simulations

Figure 5-4 shows the results of ultrasonic modelling and illustrates the change in beam shape between the isothermal case (top) and after using the thermal zone map (bottom). The modelling confirms the TWI prediction that there is a marginal change in echo amplitude but a geometrical distortion of up to 5mm.

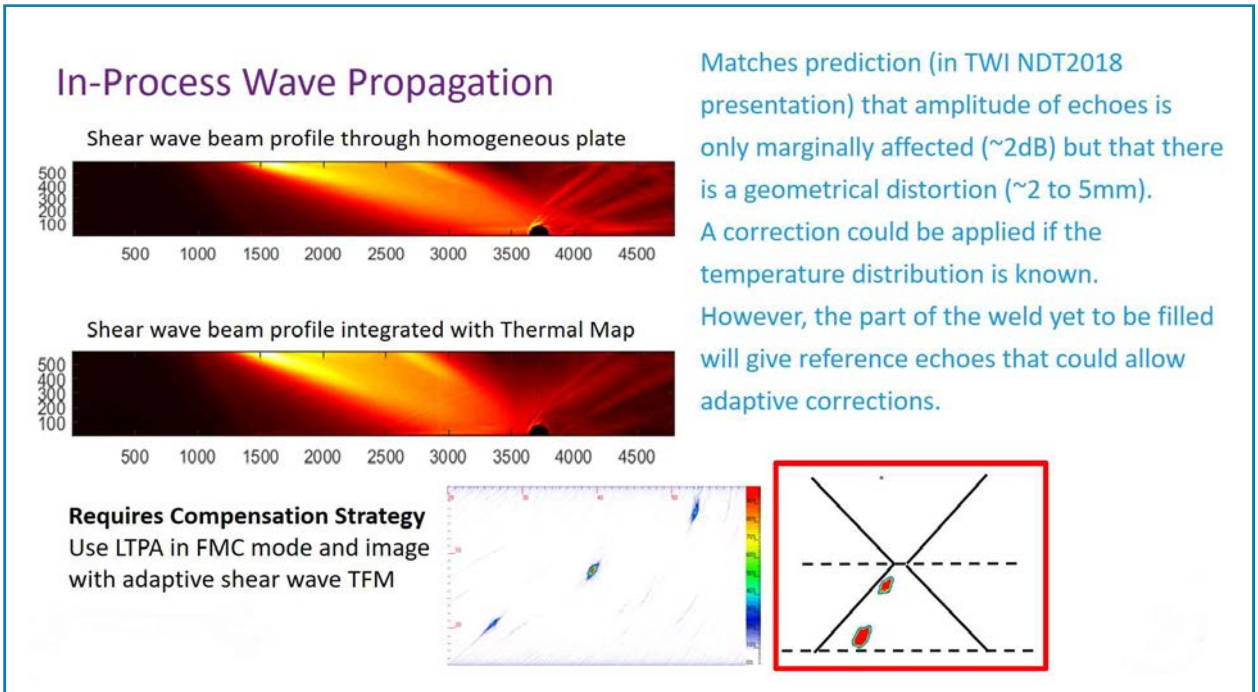


Figure 5-4 Beam propagation simulation for isothermal material (top) and with thermal gradients (bottom)

5.2.2 Results of elevated temperature imaging on the Staircase reference specimen

Data collection and imaging were performed at room temperature and elevated temperatures to assess the geometrical distortions in practice. In particular, it was important to see whether the distortion is primarily a shift, allowing the corrections to be done by aligning the echoes from the un-welded interface with their expected location.

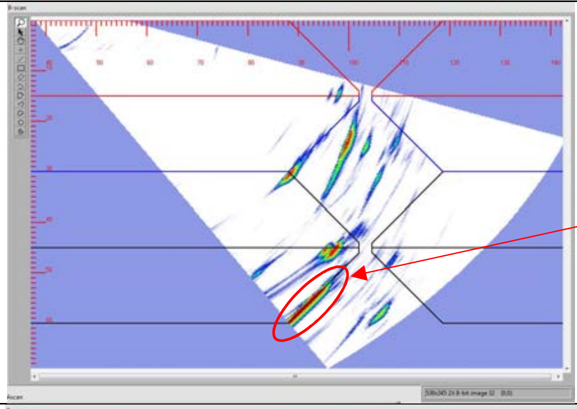
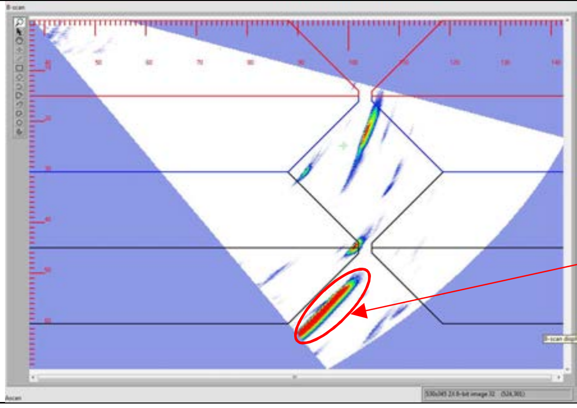
The approach adopted was:

- The array and wedge were placed on Step 2 of the Staircase test block using high temperature acoustic couplant, and a reference scan was acquired at room temperature (21.6°C) as measured using a hand held thermocouple probe.
- The location on the block was marked so that the array and wedge could subsequently be replaced at the same position during the rest of the tests.
- The array & wedge were removed and then the pre-heater blanket was used to raise the temperature of the staircase test block to 160°C and then the blanket was removed allowing the block to cool.
- When the temperature reached 150°C, the array and wedge were replaced on the block where they were clamped. Images were then acquired at intervals, recording the temperature at the mirror image across the weld matching the same point as the centre of the wedge.
- After 6 minutes, the array and wedge were removed and allowed to cool down for 10 minutes.
- The wedge was then replaced, the elapsed timer reset, and more images acquired.

Table 5-1 shows the results representing the two extremes of temperature. In both cases, the temperature distribution was almost uniform throughout the sample and, because the elevated temperature frame was acquired a few seconds after placing the array and wedge, there is likely to be little temperature gradient within the wedge.

In both cases, the images were acquired using velocities matching those at room temperature, namely wedge velocity=2470m/s and steel shear wave velocity of 3240m/s. The propagation distance to the reflector is around 85mm. At 150°C, the shear wave velocity drops to 3103 m/s and so the displayed range (assuming the original velocity) would increase to about 88.7mm. This suggests that correcting for the change in velocity would remove much of the misalignment and so geometrical errors can be tolerated.

Table 5-7 B-scan images taken at room temperature and at elevated temperature

Frame	Elapsed	Temp	Image	Comment
Ref		21.6°C		Reference feature is aligned with overlay
A0	5.24s	150°C		Reference feature is now shifted by around 3mm in range

5.3 Hardware setup to address the challenges

5.3.1 Robotic cell for in-process welding and ultrasonic inspection

The University of Strathclyde has a robotic cell for TIG welding and this has been adapted by means of a second robot for implementing the ultrasonic inspection.

The weld robot is a 6-axis Kuka KR5 ARC HW with a KRC2 controller. As well as the TIG weld head, the weld robot has a laser profiler and a video camera to monitor the weld pool.

Pre-heating can be applied via resistance blankets driven from a DHC65150 power unit from Thermal Hire Ltd.

The inspection robot, used to place the ultrasound array sensor head, is a 6-axis Kuka KR6 R900 with a KRC4 controller.

Figure 5-5 shows the robotic cell with welding and inspection robots.

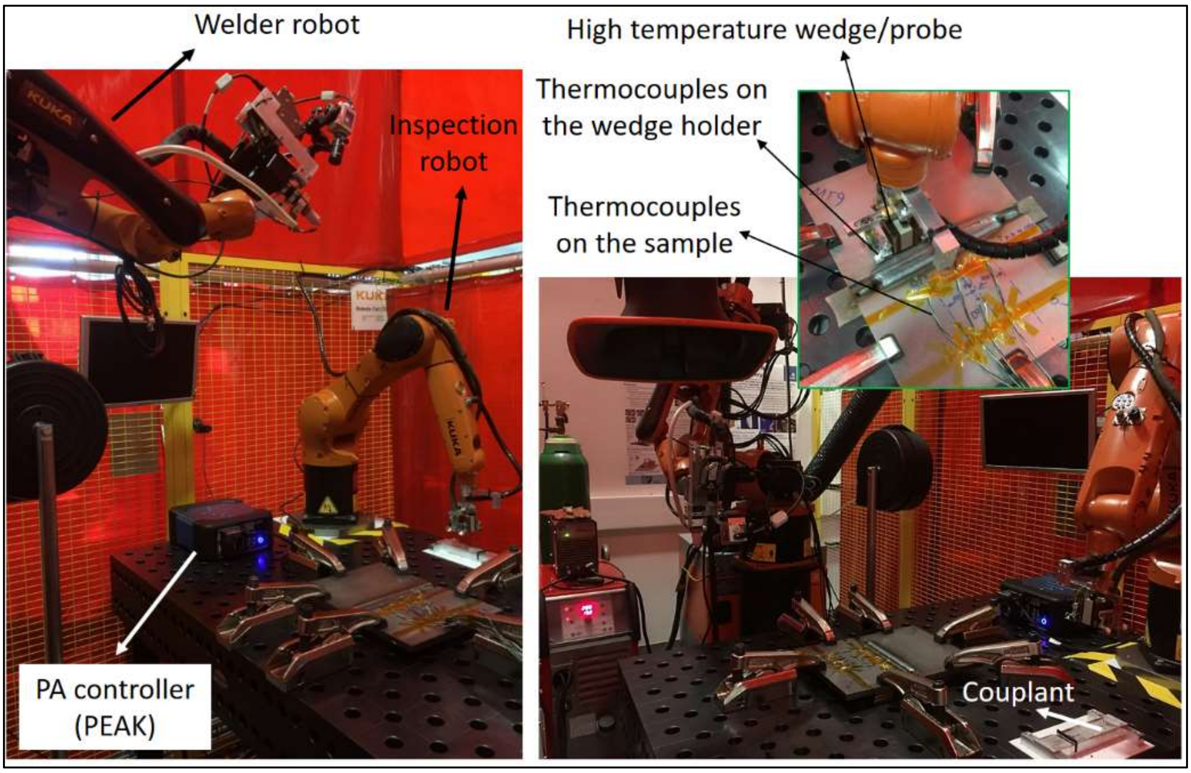


Figure 5-5 In-process inspection of multi-pass robotic welding by high temperature wedge and phased array

Real-time synchronizing and control for the Kuka Robots and Welding Control unit is via LabVIEW™ code (LabVIEW 2017-32bit) running on a cRIO-9038 from National Instruments. The cRIO controller also has a 16-channel thermocouple interface for monitoring temperatures from both the array head and for any thermocouples welded onto the top surface of the weld parent material.

5.3.2 Ultrasound sensor (array + acoustic wedge)

Commercially available ultrasound arrays are recommended to operate below 60°C. For weld inspection, they are mounted on acoustic wedges so that they only generate angled shear waves for inspecting the weld. The wedge therefore also acts as a temperature barrier and so operation on inspection surfaces above 60°C is possible. Olympus has developed a range of elevated temperature wedges manufactured using an amorphous thermoplastic polyetherimide resin called ULTEM™, and they can operate at surface temperatures up to 150°C (4). The array and high temperature wedge selected are shown in Figure 5-6.

While ULTEM's insulating properties are used to protect the probe from heat, heat dissipation is also important to enable a longer inspection period. When the ambient temperature is 25°C, the wedge can be kept in contact with a 150°C surface for a maximum of 10 minutes. It takes an additional 10 minutes for the probe and wedge to cool. As the temperature increases from 24 °C to 150 °C, the ultrasonic velocity of the ULTEM wedge material drops from 2470 m/s to 2270 m/s, while the shear wave velocity in steel drops from 3240 m/s to 3103 m/s. The appropriate values for the operational temperature need to be used when calculating the appropriate electronic steering and focusing delays to transmit and receive beams from the desired locations.

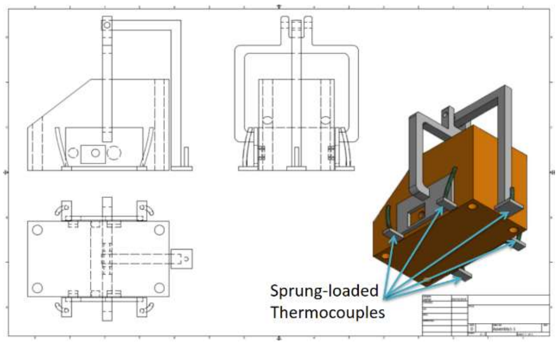
Figure 5-6 Ultrasound array (5MHz 64 element) mounted on 55° shear wave ULTEM™ wedge

Most ultrasound arrays use the piezoelectric effect to perform transduction from electrical to mechanical energy on transmit, and the reverse on receive, as this is the most efficient mechanism. The most sensitive piezo materials have a Curie Point just above 100°C and so have to operate in a temperature range below around 80°C, although in practice an upper limit of around 60°C is common to prolong the life of the array. For optimum sensitivity and bandwidth, the transducer material is diced and filled with an inactive epoxy matrix to produce a piezo-composite structure, and the operational temperature range of the epoxy imposes additional limits.

Transducers and arrays can be made with materials that have much higher Curie Points but they are much less sensitive. The only ones that have reached the market are single element devices, and are usually intended to be permanently installed for monitoring applications, so not suitable for scanning. A recent spinout company from the University of the West of Scotland (Novosound) has developed a proprietary thin film technology that retains transduction sensitivity to 350°C, and potentially up to 450°C. The elements of an array can be made by printing, and the result is a flexible array. These too have significantly reduced sensitivity compared to their piezo-composite equivalents, but it is possible to mitigate against this disadvantage by using spread spectrum excitation and matched filtering. The University of Strathclyde has a Phased Array Controller that can use coded excitation and filtering to achieve significant (~18dB) signal to noise improvements, so this allows this new technology to be investigated further. At present however, the arrays are at a very early stage of development, with none available for evaluation, and so these have been ruled out for the current phase of work.

Other high temperature solutions, such as Electro-Magnetic Acoustic Transducers (EMATs), are available but they are much less sensitive and more difficult to generate the required angles. In particular, they are less suited than arrays to the separate pitch-catch configurations that are needed for narrow-gap welding. It is possible that they may evolve to be useful in the future but are not at this point yet.

For this phase of work, the only solution is the array and wedge that can tolerate 150°C surface temperatures. The combined assembly is mounted in a frame that attaches to the end effector of the inspection robot. The mounting includes sprung-loaded thermocouples that contact the surface before the wedge. The thermal distribution from weld-modelling software is used to predict when the surface temperature is safe for placing the wedge, but the thermocouples distributed around the mounting provide a further level of safety. The outputs from these thermocouples can also be used for a 4-point measure of temperature to assist in any calculation of thermal gradients. Figure 5-7 (left) shows the ultrasound sensor head comprising array, wedge, thermocouples and mounting. These can be combined in pairs, as shown in Figure 5-7 (right), on the robotic end effector to inspect from both sides of the weld, and in pitch-catch mode through the weld.



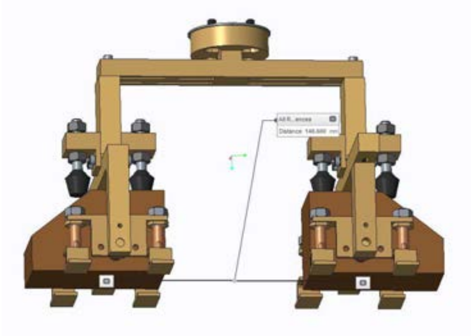


Figure 5-7 Ultrasound sensor head – acoustic wedge with sprung thermocouples (left) and twin head (right)

5.3.3 Ensuring interference-free data acquisition

The welder and the robots have the potential to generate strong electromagnetic interference that can affect the quality of the data being collected by the ultrasound phased array system. Initial tests showed that the interference generated when the arc strikes was sufficient to switch off the phased array unit and also reset the controller module used to collect the thermocouple outputs. The latter was resolved by modifying the code to detect when it was subject to a reset condition, and to re-initialise all the relevant parameters. Optimising the location of the Phased Array Controller (PAC), and the earthing/shielding arrangement of the array and controller avoided this being reset by the arc striking. There was still electrical interference on the output of the PAC from both welder and robots, but this was outside the bandwidth of interest in the ultrasonic data and was successfully removed by high-pass filtering of the data.

5.3.4 Modification of imaging and analysis for in-process inspection of multi-pass welding

Commercially available imaging systems use simple scan-conversion algorithms to show the sequence of data samples in each beam into a geometrically correct map. The acoustic wedge and the parent material are each treated as a uniform block of specified acoustic velocity, and so the start point, angle and scaling of each beam vector is determined from these velocities.

The beam focus and steering delays used by the phased array controller for each element of the array also make use of these acoustic velocities to ensure that the beam pulse follows the same direction. At elevated temperatures, which can be verified by the thermocouple sensors on the array mounting assembly, both the phased array beam delays and the scan conversion geometry can make use of amended velocities.

Temperature gradients, either in the acoustic wedge or in the inspection material, will bend the beams. The gradients, and therefore the amount of bending, can be derived from verified weld simulations. There is therefore a need to have a scan-conversion algorithm that supports this beam bending. This has been implemented in a new LabVIEW library (.lvlib) which is still fast enough (~5ms for a typical high-resolution image) for the most extreme data acquisition and display rates. The resulting image is then imported into the LabVIEW Vision module, where overlays can be used to indicate the pre-weld geometries, assisting analysis of the echoes, as shown in Figure 5-8.

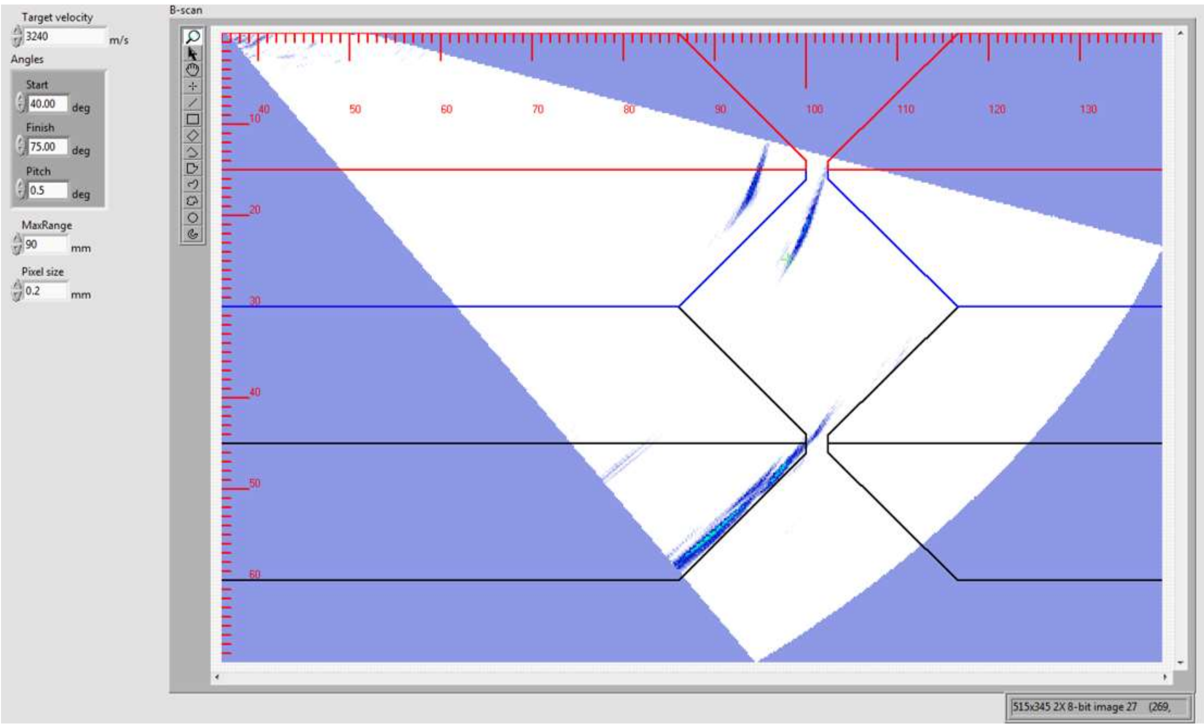


Figure 5-8 Scan-converted sector B-scan display with overlay showing pre-weld geometry

The LabVIEW Vision module also supports localised Regions of Interest (ROIs) which can be used to mask the false-positives that will result from the un-welded interfaces of a part-filled weld.

Figure 5-9 illustrates the standard inspection case, where a complete weld is inspected and a LOF defect, shown in blue, is identified and correctly reported.

Figure 5-10 shows the in-process inspection where the weld is good, but the remaining bevelled surface produces LOF-like echoes, shown in red, which would be false-positives if reported.

Figure 5-11 shows the in-process inspection where the weld is poor. There are both true-positive LOF indications in blue, which must be reported, and false-positives from the incomplete weld surface in red, which must not.

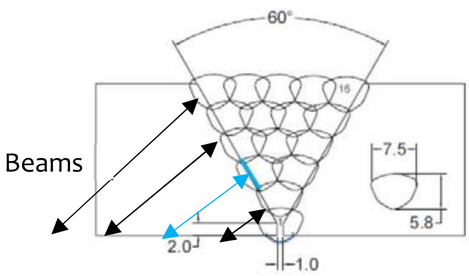


Figure 5-9 Standard Inspection: Fully complete weld and correctly reports LOF defect (blue)

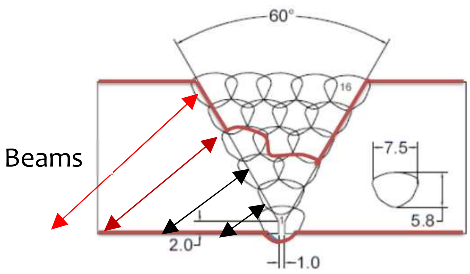


Figure 5-10 No defect during welding: Part-filled weld which produces False-Positive LOF defect (red)

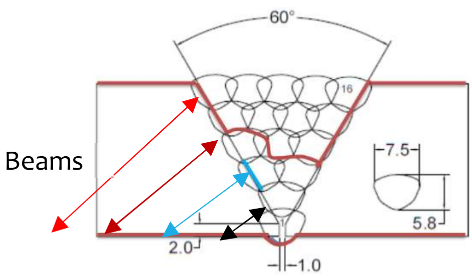


Figure 5-11 Defect during welding: Need to detect LOF defect (blue) whilst rejecting False-Positives (red)

5.4 Proposed sequence for in-process inspection of multi-pass welding

The surface temperature limit of 150°C, for state of the art commercially available arrays and wedges, imposes constraints on the inspection sequence. This leads to the proposed flow chart, shown in Figure 5-12, for in-process inspection.

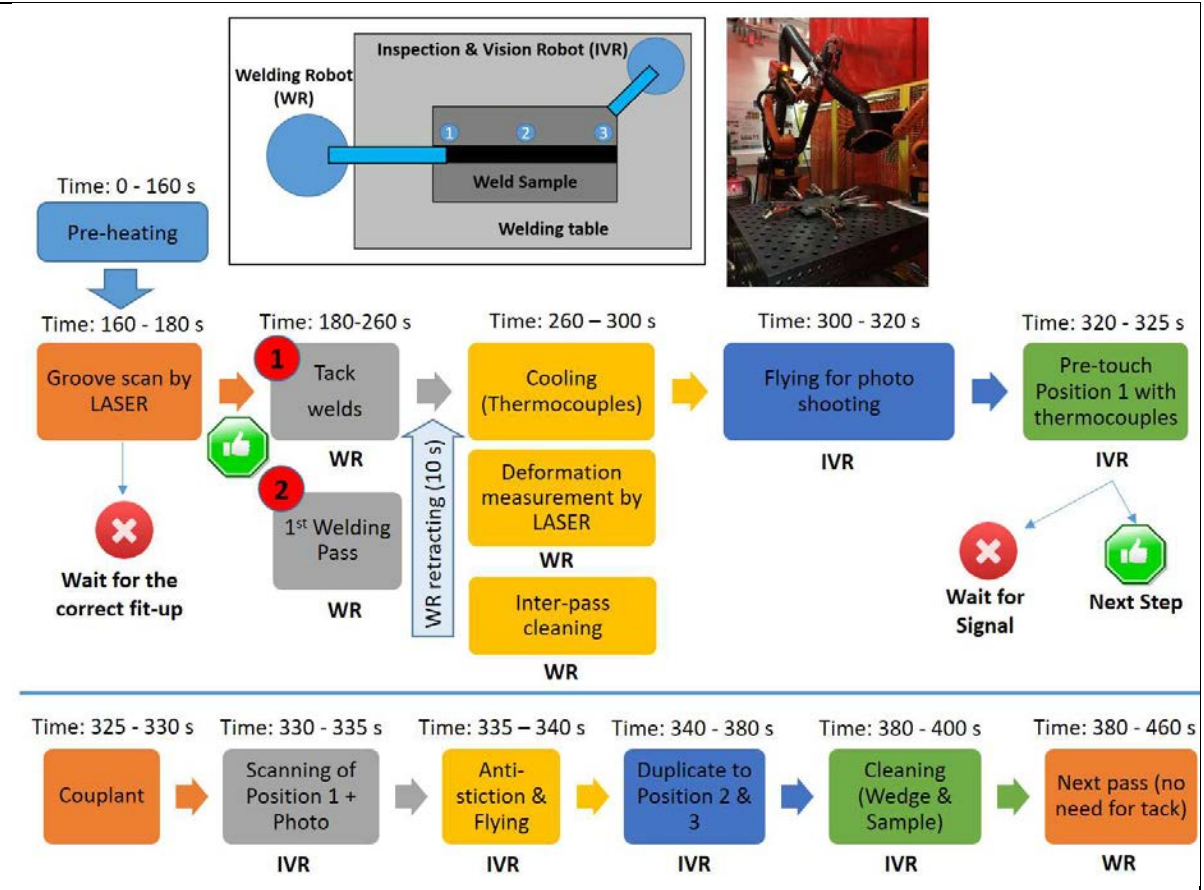


Figure 5-12 Flow chart of In-Process Inspection of multi-pass robotic welding

6 End MRL/TRL level

The results of the work covered in this report has achieved the thresholds required for TRL level 3 and significant progress towards achieving TRL level 4. Most of the requirements for MRL level 3 have also been achieved and a start made towards MRL level 4. The justification for these values is shown in Appendix 1.

6.1 Potential industrial impact

The potential industrial impact is significant as it offers similar benefits to any of the industries involved in joining and welding. Typical examples include:

- Welding with configurations other than narrow-gap, such as J-groove and V-groove.
- New techniques such as Additive Manufacturing (AM) of metals, such as Wire + Arc Additive Manufacturing (WAAM), where as yet there are no inspection standards.

Any welding process that follows the international inspection standards will suffer from the same requirement to delay final inspection until after the specified time to allow any cold-cracking to develop. This can be up to 96 hours. This not only precludes any early intervention on the weld process, if inter-pass defects are being generated, but also enforces the movement of the part between manufacture and inspection sites. These increase inefficiency and manufacturing costs and so improvements to both are expected, encouraging industrial uptake.

Any in-process manufacturing really needs to be accompanied by in-process inspection, and this requires the challenges addressed in this project, such as high temperature inspection, to be resolved. Indeed, the absence of such an in-process inspection capability could be regarded as a hurdle that is limiting the adoption of automated manufacturing processes. Automated manufacturing + inspection will improve the reliability and repeatability of the inspection, by reducing the effect of human factors. It also provides documented results, which are especially important in critical structures, an area where ultrasound inspection has had difficulty in matching the records from radiography.

Some applications, such as pipe welding on ships, are particularly dependent on fast and reliable inspection as part of the manufacturing process to be able to lay a sufficient length of completed pipe for commercial viability. They are therefore likely to be early adopters of in-process inspection.

There has also been a spin-off from the very flexible robotic cell for welding with in-process inspection that was optimised for the SIMPLE program. The robotic welder is able to generate specific types of defects, one of which is the cold-cracking (hydrogen cracking) that requires the delayed inspection. The inspection robot is able to deploy the ultrasonic array sensor and to log the resulting images over an extended period, allowing for the development of the crack to be monitored. Potentially this allows novel techniques, such as non-linear imaging, to be investigated, to see if they can provide an earlier detection capability. In addition, since all the weld parameters during manufacture are logged, they can be examined retrospectively, to see if there are any early indications that can be used for optimising the welding process. If any of these approaches are able to reduce the time between manufacture and the final inspection, there will be a significant improvement in efficiency and a matching cost saving.

6.2 Future work

Extension of existing scope to raise it to higher TRL/MRL levels

- Formalising & verifying the calibration process to ensure that it covers the extended temperature range. This is needed for collecting fully calibrated data that will be required to support the eventual extension of the inspection standards to cover in-process inspection.

- Verify detection on the full range of possible defects. Again, this is required for fully populating the database of defects to support extension of the inspection standards.

- Extend to use two arrays, allowing for simultaneous inspection from both sides of the weld, as well as supporting the dual probes needed for Time-of-Flight Diffraction (TOFD) inspection.

- Automation of the detection of the weld-preparation features to enable automated adaptive correction of the imaging geometry for temperature. This then provides fine control of the region of interest used for thresholding the data for automated defect detection.

- Use of Full Matrix Capture (FMC) and Total Focusing Method (TFM) reconstruction to allow adaptive beamforming which compensates for both raised temperature & gradients, rather than just relying on correcting the image geometry by scan conversion compensation. FMC + TFM generates both transmit and receive beams synthetically as a post processing operation and so offers the potential for enhanced resolution due to the optimised focus achieved by compensating for the temperature gradients.

- Evaluate for early detection of hydrogen cracking using synthetic defects. This requires monitoring of crack growth for an extended period after completion of the weld, with up to 96 hours being specified in the inspection standards. Gathering evidence of the crack onset time will potentially allow a reduction of this wait period, again contributing to a reduction in manufacturing costs.

7 Recommendation for further research and development

7.1 Extension of the application to similar inspection configurations

- Application to other welding configurations, such as pipeline welding.
- Additive Manufacturing of metals involves many of the same requirements (in-process inspection for integrity verification) with similar constraints (high temperature, couplant-free), and would benefit from the same techniques.

7.2 Inclusion of relevant outputs from parallel research work

The demonstrated solution is based on adapting current commercial state-of-the-art devices to address the technical challenges in an appropriate timescale. As previously stated, there has already been decades of work on high temperature array solutions but these remain at low TRL levels. They do however address the limitations of the proposed solution, including: desirability to operate at surface temperatures above 150°C; ease of scanning along the weld rather than spot sampling; potentially avoiding the use of acoustic couplant so minimizing requirement for removal of the residue after inspection.

The University of Strathclyde has been developing a high temperature version of a "roller probe". The low temperature versions on the market offer a means for an ultrasonic array to be scanned over a region, at speed and without the use of couplant. These features are all highly desirable for in-process inspection and so, when the high-temperature version becomes sufficiently mature, it would be very desirable to evaluate it on the SIMPLE application. Figure 7-1 shows the typical architecture of the roller probe.

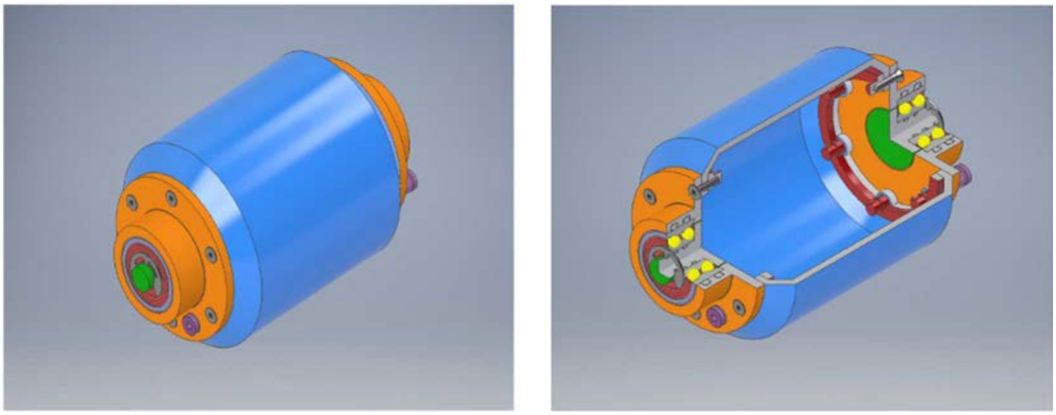


Figure 7-1 Roller probe (left) and cutaway (right) to show internals (without the array)

7.3 Route to industrial adoption

The in-process inspection is currently at a low TRL/MRL level and so the initial route towards eventual industrial adoption is likely to be through, and in collaboration with, the SIMPLE partner organisations. Peak NDT already supplies inspection equipment worldwide, both direct and through agents, and so is in a good position to assist in moving the technique into industrial use.

The University of Strathclyde is already collaborating with Cranfield University to develop inspection techniques, and eventually standards, for Additive Manufacturing (AM). As already stated, in-process inspection is likely to offer major benefits for AM, and so the WAAM cell being assembled at the Advanced Forming Research Centre (AFRC) is likely to be an early adopter, also providing a demonstrator facility for encouraging industry uptake.

The University receives regular enquiries about difficult applications and one of these was from a company offering pipeline weld systems for pipe-laying ships. They saw the robotic cell in operation and anticipate considerable benefits from adding the in-process inspection to their existing welding system. This application area is therefore another potential route for industrial adoption.

7.4 Engagement with industry/academia

During the project, the existing contacts with key industrial suppliers, such as Peak NDT (Phased Array Controllers), Olympus NDT (Phased Arrays, Acoustic Wedges and high temperature couplants) and Kuka (Robots) have been affirmed and extended. All have expressed an interest in continuing this collaboration in any further work through to industrial adoption.

The University of Strathclyde also has links with other partner organisations on related work, in addition to those already within the SIMPLE projects (e.g. TWI). These contacts, such as the University of Manchester's weld profiling team and TPS Weld Tech, have provided useful advice on the welding. Cranfield University, and their spinout company WAAM3D, are involved with Strathclyde on collaborative projects for NDE on Additive Manufactured (AM) parts, and this has guided the approach for extending SIMPLE's in-process inspection techniques on AM components.

The University of Strathclyde is also a member of relevant research groups, including the UK's Research Centre for NDE (RCNDE) and the Advanced Nuclear Research Centre (ANRC). The capability for in-process inspection has been showcased at recent meetings of both these groups, with favourable feedback leading to potential future collaborations.

7.5 Conclusions and acknowledgements

The new issues associated with in-process inspection of multi-pass welding have been laid out. Approaches to address these issues have been outlined, and those that can be implemented within the SIMPLE project timescale have been tried out in the extended robotic welding cell at the University of Strathclyde. Appropriate test blocks have been manufactured and experiments have been carried out, confirming that the high temperature inspections are feasible. These confirm the feasibility of the approach and a flow chart for the in-process inspection has been presented.

The work carried out was over a wide range of disciplines including welding, robotics, ultrasound data collection and imaging, NDE analysis, image processing, system hardware and software integration, as

well as support from technical and mechanical staff. The University of Strathclyde's Centre for Ultrasound Engineering (CUE) has all of these capabilities and the resulting work is therefore a whole team effort. In particular, the following personnel contributed: Yashar Javadi, Momchil Vasilev, Ehsan Mohseni, Charles MacLeod, Euan Foster, Charalampos Loukas, Rastislav Zimmerman, Zhen Qiu, Randika Vithanage, and Dave Lines.

8 References

1. **BS EN ISO 17640:2010.** ***Non-destructive testing of welds — Ultrasonic testing — Techniques, testing levels, and assessment (ISO 17640:2010).*** **s.l. : BSI Standards Publication, 2010. BS EN ISO 17640:2010.**

2. BS EN ISO 13588:2012. ***Non-destructive testing of welds — Ultrasonic testing — Use of automated phased array technology (ISO 13588:2012).*** **s.l. : BSI Standards Publication, 2012. BS EN ISO 13588:2012.**

3. BS EN ISO 19285:2017. ***Non-destructive testing of welds — Phased array ultrasonic testing (PAUT) — Acceptance levels (ISO 19285:2017).*** **s.l. : BSI Standards Publication, 2017. BS EN ISO 19285:2017.**

4. Ultrasonic phased array wedge for inspecting high-temperature parts up to 150°C. ***Olympus Industrial Resources - Applications Notes.*** **[Online] [Cited: 10 June 2019.] https://www.olympus-ims.com/en/applications/ultrasonic-phased-array-wedge-for-inspecting-high-temperature-parts-up-to-150c/.**

E. Visual Sensor

Report No: 32111/3v2/19

August 2019

For: Nuclear AMRC

SIMPLE Work Package 2.2.4 - Visual System Technical Report

TWI Ltd

TWI Ltd (TWI) is one of the world's foremost independent research and technology organisations, with expertise in solving problems in all aspects of manufacturing, fabrication and whole-life integrity management technologies.

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The company operates a management system certificated by LRQA to BS EN ISO 9001 as well as for health and safety (BS ISO 45001) and environment (BS EN ISO 14001).

(See inside back cover TWI Management System.)

TWI Report: SIMPLE Work Package 2.2.4 - Visual System Technical Report

Report No: 32111/3v2/19

Date: August 2019

Prepared for: Nuclear AMRC
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TWI Endorsement

This report has been reviewed in accordance with TWI Policy.

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Contents

1 Technical challenge and first principles

1.1 Requirement for visual monitoring of arc welding

Nuclear plant manufacture necessitates welding of thick-walled (~100mm) pressure retaining components. This can be performed by various welding methods, such as electron beam (EB) welding, or Narrow Groove Gas Tungsten Arc Welding (Narrow Groove GTAW). EB welding is typically performed in a single pass through a closed square butt joint, but Narrow Groove GTAW requires multiple layers of weld metal to be deposited within an open groove.

Given the quantity of weld metal to be deposited, Narrow Groove GTAW of thick-walled pressure vessels can require days to weeks to complete a weld. If defects are introduced at the root or an early pass, and not detected during welding, a significant amount of material needs to be removed via a machining process in order to allow repair of the defect. This adds additional time and cost that can be greater than the original manufacturing process.

It is necessary therefore to both minimise any possibility of introducing defects via non-optimal welding, e.g. by poor weld pool placement leading to a lack of fusion, and to detect potential defects as early in the process as possible. This is partly done by staged non-destructive examination (NDE), e.g. by using radiographic inspection on the first few layers of the weld, while it is only partially filled, so that any root repair procedure does not require removal of full thickness material above that point. However, this can still result in potentially a lengthy repair procedure if a defect is not detected during welding. As such, it is desirable to have some form of weld monitoring that is performed in-process at all possible times.

1.2 Existing arc welding monitoring solutions

The current solution for monitoring of the welding process uses operator observation of the production of the weld, including watching the tungsten electrode, arc, weld pool and weld bead deposited. This is done by either one or two welding operators constantly looking at the weld pool. If necessary, they can then interrupt the welding process to perform an in-process repair procedure, often a simple burr-grinding or similar machining operation, without significant loss of productive time.

Observation of the weld pool is done through a glass welding filter to eliminate the majority of the arc brightness as well as damaging infrared and ultraviolet radiation. While this works as a solution, it is better suited for either short-term welding, or manual welding. For Narrow Groove GTAW, the observation is mostly passive, with only slight adjustment to the tungsten electrode in a direction perpendicular to travel if required.

This means that it is often more useful for observation to be performed on a monitor/screen, with images delivered from cameras located on the welding head. These can be mounted both ahead and at the rear of the arc, allowing an operator to observe two locations simultaneously, which would not be possible with direct visual observation. It also allows the use of high definition, high dynamic range (HDR) cameras, which can convert a high brightness signal to something that is more easily visualised by an operator. For example, it may prove easier to separately observe the central plasma column and the surrounding flare through a camera which can be adjusted to changes the threshold of different brightness levels as required.

The use of camera systems also reduces the risk of potential eye strain or exposure to UV, and also allows welding to be performed remotely, for example with operators sitting at a controlling terminal next to a rotating platform on which welding occurs. A camera system will also record the welding process, such that if a defect is detected at a later time, the recorded video of that stage of welding can be played back, to allow forensic analysis to be undertaken.

1.3 Automated visual weld monitoring concept

As noted earlier, Narrow Groove GTAW of thick-walled components in general takes a long time to perform. This means that operators will need to observe welding for up to (and potentially above) an hour for every single pass (depending on component diameter and travel speed) and undertake this multiple times over a single welding shift of eight or more hours. Fatigue and operator distraction can become a factor in this process, which can result in defects not being observed and welding not being interrupted, such that they are not removed in-process. It would, therefore, be preferable to have a solution that is guaranteed to continually observe the process.

As stated, the industry standard approach is to perform this form of mechanised welding with operator observation through a visual image displayed on a screen. This means that there is already a base level of information being recorded as a standard operating activity during the process that is available for some form of analysis. This can potentially be used for automated analysis by a computational system, while still being displayed to an operator as a backup.

Given the visual data is available, the most suitable solution is to attempt to make use of this visual data in the same manner an operator does, but without the issues with fatigue or distraction. An automated system can collect visual data (e.g. via the attached camera) and then perform some form of image analysis, via algorithmic processing of a digital signal. This would essentially then be able to "see" the welding process and determine if it was optimal or non-optimal.

In this project, image analysis is performed using neural networks. These are software packages that are intended to partly simulate the manner in which the human brain processes information (hence "neural"). They receive input information, in the form of language, number strings or images, and perform a range of operations on these inputs, depending on the precise structure of the network.

For this application, the intent is to have the network receive an input in the form of a series of images (video "frames"), similar to how the human brain processes motion. Each image is then analysed via an image recognition algorithm to segregate it in to a set of pre-determined categories. These would be based on the conditions that an operator would potentially observe, such as optimal welding, lack of fusion, burn-through or similar. If a specific number of non-optimal categorised frames are detected, the welding process can then be interrupted.

2 Starting TRL and MRL level

Prior to this project, the overall TRL and MRL of this combination of equipment, application and capability was level 2. The justification for these values is shown in Appendix 1.

As an overview, certain elements of the process are generally well understood and some have been applied in a partial manner. The welding camera used to collect the visual images that are analysed is "off the shelf" equipment, sold specifically for observation of welding, and requires no modification to be able to send images to an algorithmic analysis tool. This camera is designed for the high temperature, high brightness conditions, and can be considered application-ready. The concept of image analysis in general has also been applied for in-process weld monitoring [1].

Neural networks have seen rather more limited manufacturing-related uptake, being primarily used and developed in more academic settings, not industrial. Some studies have been performed using these for control of robotic welding [2] and image analysis of laser welding [3] but none have been used specifically in the manner intended in this body of work. However, neural networks in general are well understood, even if they require a certain level of technical knowledge to assemble and operate.

3 Overview of technical challenge for industry

3.1 Evolution from first principles

Existing technologies were available for some individual aspects of the equipment setup.

The vision system consists of multiple components, those being:

- Xiris XVC1000 camera
- Power over Ethernet (PoE) injector
- Lens components (75mm lens + 20mm spacer)
- Windows-based PC

The image analysis neural network was generated using a collection of software tools, those being:

- Cuda Toolkit
- Python
- PyTorch/TensorFlow
- Xiris Software Developer Kit (SDK)
- XVC-1000 WeldStudio
- Unix-based PC

To the authors' knowledge, no instances of system assemblies similar to this have been reported in the literature, so it was necessary to construct a software framework that could both decompose the videos into individual frames, generate a neural network that was capable of analysing the frames and then categorise the information following training of the neural network.

Video recording was performed using the camera manufacturer's proprietary software (XVC-1000 Weldstudio), which required no further development. Examples of the video recording setup are shown in Figure 3-1 and Figure 3-2.

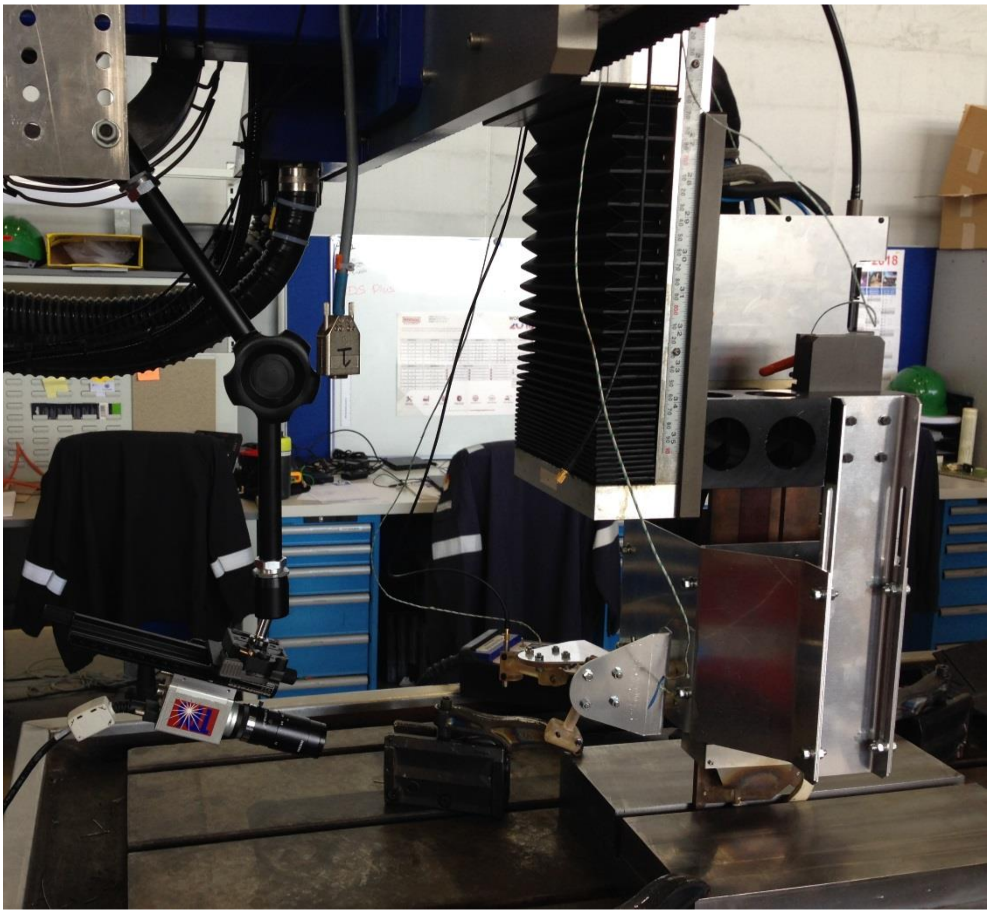

Figure 3-1: Visual monitoring setup.

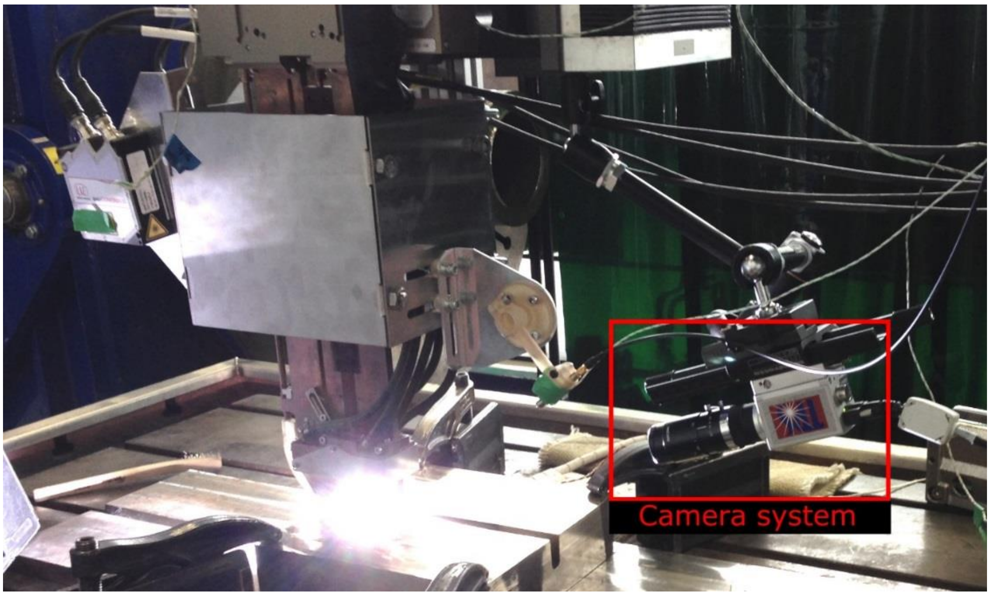

Figure 3-2: Visual monitoring during welding.

Videos were broken down based on the processing power of the PC driving the camera, with frame rates varying between 25-50 Hz, limited by data transfer and storage capability of the PC.

The neural network was developed internally, using the software listed above. The authors believe this approach is entirely novel.

3.3 Work conducted and the development path

3.3.1 Initial system assembly

The weld monitoring and image analysis system was assembled by TWI from the component parts, using the camera manufacturer's SDK to ensure the transition of the videos through to the analysis software.

This generated a workflow path:

- Generation of weld samples with both optimal welding conditions and non-optimal welding/defects
- Collection of videos
- Decomposition of videos into individual frames
- Categorisation of frames by visual/macro inspection to allow training of the neural network
- Separation of frames into training (75%) and testing (25%) sets
- Preparation of frames via cropping (eliminate extraneous information) and subsampling (reducing process time)
- Forwarding of training frames to the neural network, with the expected output specified
- Multiple loop propagation of training frames through the neural network and self-modification of the neural network to generate output in line with expectations
- Forwarding of testing frames to the neural network, and comparison of the generated output with visual(/macro) inspection
- Calculation of relevant accuracy metrics

Further details are provided in Sections 3.2.6 and 3.2.7 on some elements of this workflow.

3.3.2 Welding process

Welding trials were performed to generate example data for the vision system, representative of the intended application. This is a Narrow Groove GTAW process, for welding of thick wall pressure vessels for nuclear power applications. The material typically used for these applications is a carbon steel (specifically ASTM SA 508), and so a carbon steel of similar composition was used for the trials. The joint preparation geometry used for the welding trials is shown in Figure 3-3. The filler wire used was a 1.2mm diameter solid wire AWS A5.18 ER70S fed into the leading edge of the weld pool, with Argon as a shielding gas. A narrow groove was machined into an 80mm thickness plate to simulate the intended geometry.

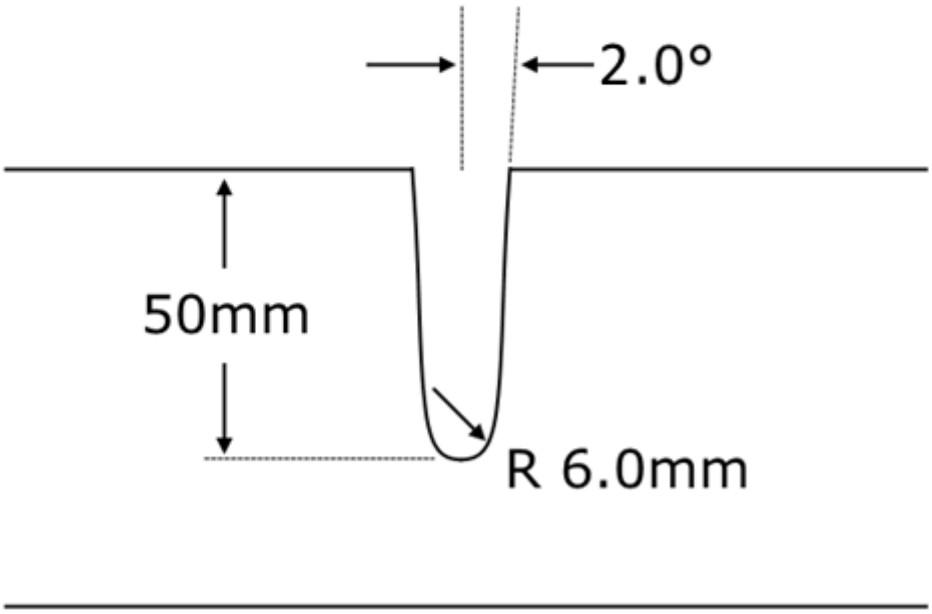

Figure 3-3: Representative joint preparation geometry.

The welding trials were performed using the camera system trailing the welding head, positioned to allow movement of the camera above the welded joint without causing obstruction. This setup can be seen in Figure 3-4.

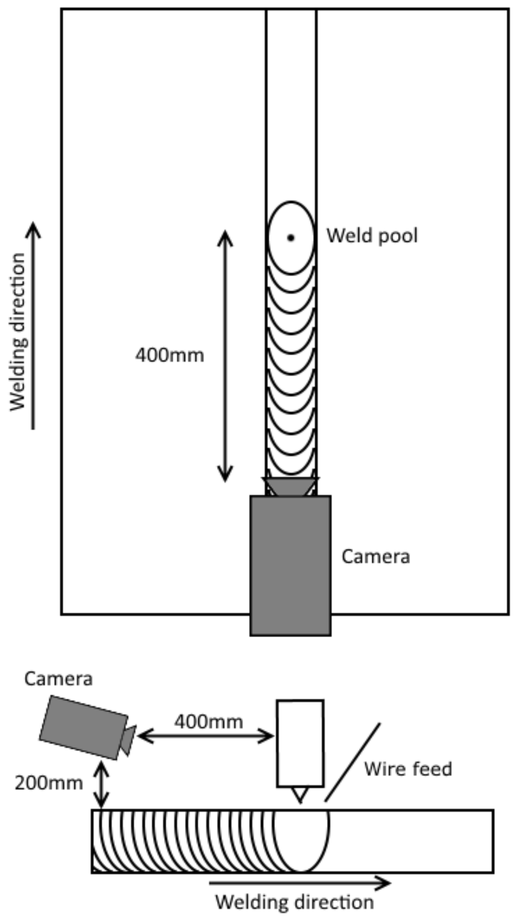

Figure 3-4: Weld camera positioning.

Examples of frames recorded during the welding process are given in Figure 3-5 and Figure 3-6.

Figure 3-5: Example video image taken during root pass welding.

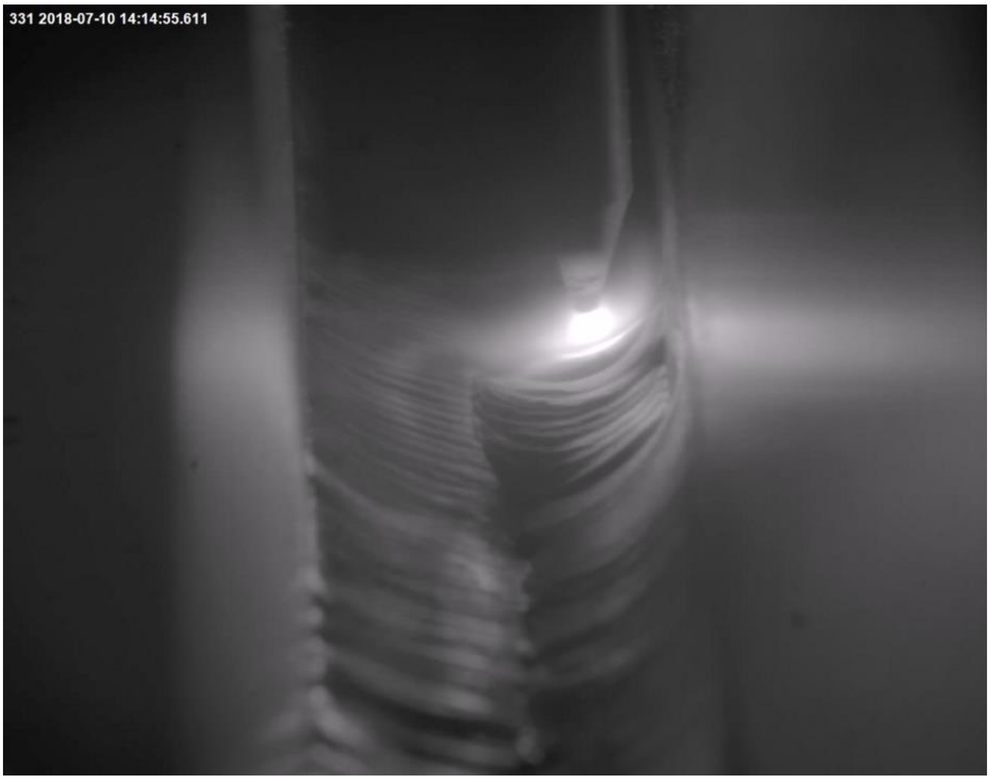

Figure 3-6: Example video image taken during sidewall welding.

3.3.4 Defect generation

Defective weld samples were produced by varying the welding parameters that would typically be altered during the welding process to ensure that the welding process remains optimal. All other welding parameters were in line with the "optimal" parameter set specified by Nuclear AMRC. Further details on specific parameters for each trial are given in Section 3.2.8.

The non-optimal conditions considered are:

- Excessive arc length
- Insufficient arc length
- Excessive cap height
- Excessive current
- Insufficient current
- Insufficient filler wire addition
- Arcing onto sidewall
- Excessive sidewall fusion
- Insufficient sidewall fusion
- Excessive travel speed

Examples of welds made with varying welding conditions are shown in Figure 3-7 and the typical effect of specific non-optimal welding conditions are given in Table 3-1.

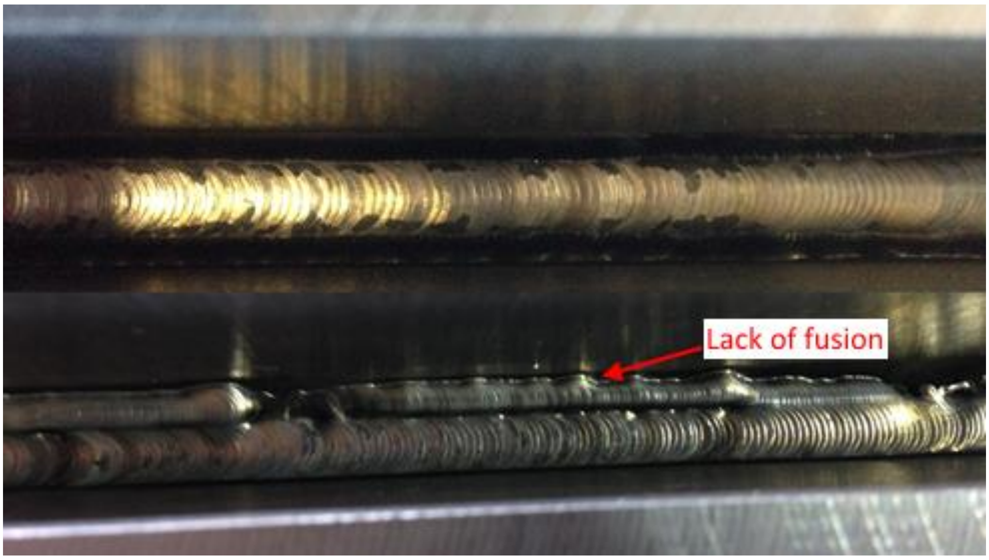

Figure 3-7: Example welds: top) "good" and bottom) "lack of sidewall fusion"

Table 3-1: Welding parameters and their effect on process instability

Welding parameter	Defect/process instability
Travel speed	Bead profile/continuity
Arc length/voltage	Bead width/arc stability
Welding current	Excessive/insufficient fusion
Wire feed speed	Bead profile/arc stability
Bead placement	Bead profile/insufficient fusion
Proximity to side wall	Excessive/insufficient sidewall fusion

3.3.5 Frame categorisation

The videos recorded during welding trials were examined visually to determine where different non-optimal welding conditions were present (either intentionally or unintentionally). Additionally, after weld completion, macro-sectioning was used to correlate internal defects with individual frames within each video.

Examples of frames selected from the videos recorded are given in Figure 3-8.

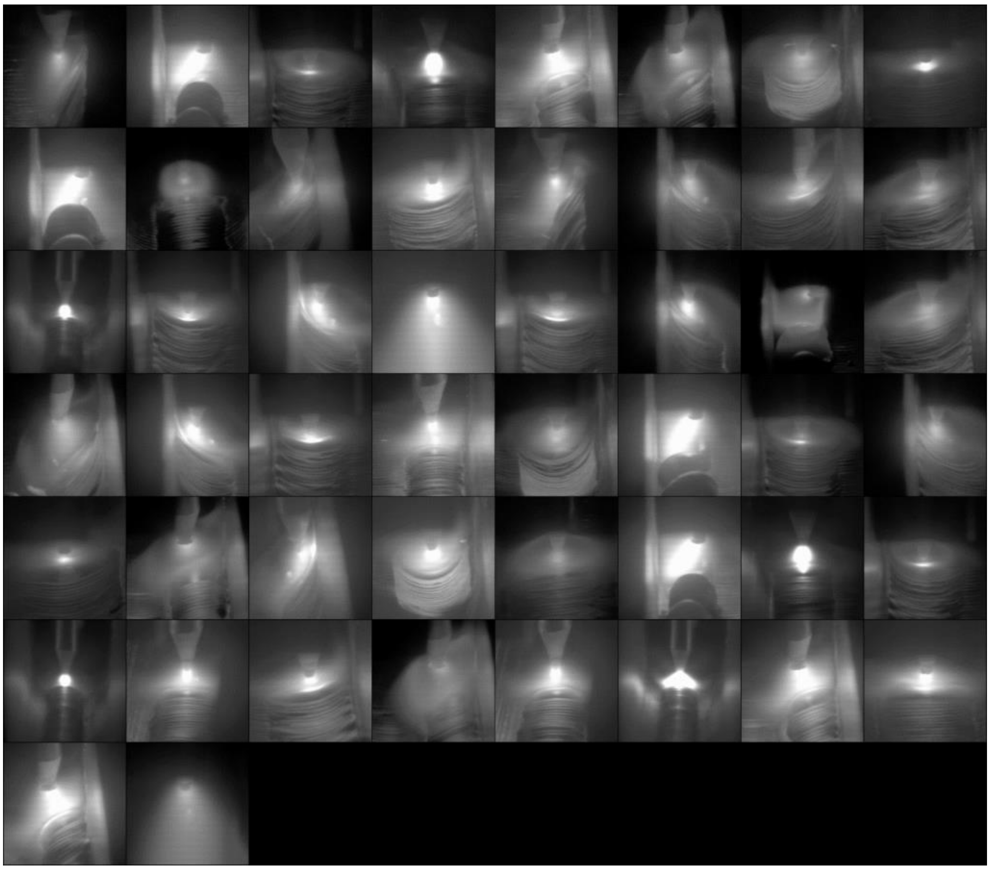

Figure 3-8: Example selected frames from videos.

3.3.6 Image preparation

The generated image undergoes a series of processing stages prior to analysis by the neural network. The first stage is an automated cropping process, based on the point of highest brightness, to reduce the image size and minimise the amount of irrelevant information, leaving a view of the arc and weld pool. This improves process speed and reduces the risk of errors in the process.

After cropping, the two-dimension image is "flattened" to generate a single string of digital values, which is then fed to the neural network as an input layer.

An example of the principle applied during this process is shown in Figure 3-9.

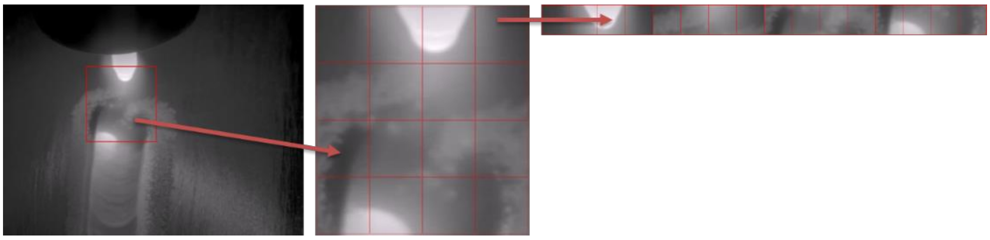

Figure 3-9: Example image processing route a) full image, b) cropped image and c) flattened image.

3.3.8 Neural network architecture

A neural network consists of an indeterminate number of hidden processing layers sandwiched between an input and an output layer. The hidden layers perform transformations on the linear input string, passing the resultant string to the next layer and so on, until it reaches the output layer. This output layer is in the form of a categorisation, with the string allocated to the optimal or one of the possible non-optimal parameter categories.

The network for this project consists of a combination of convolutional fully connected layers. The convolution layers filter the input image and resultant matrix of values into a smaller image with increased complexity, and the fully connected layers analyse it as a linear string, resulting in the output of a single value, which correlates to one of the categorisations. 55 neural network configurations were tested during the overall project, with the most accurate configuration being used. More specifically, the layers are:

- 1st layer: 160000 node (400x400 pixel) input layer
- 2nd layer: Maximum pooling layer, with a [5,5] size, 5 stride kernel, generating a 19200 node output
- 3rd layer: 256 size fully connected matrix multiplication layer
- 4th layer: 128 size fully connected matrix multiplication layer
- 5th layer: 8 size output layer

3.3.9 Training set + training methodology

The selected elements of each video are then separated into these categories as a complete dataset of categorised images. This dataset of images is then further split into a training and testing subset.

The training subset is used to "train" the neural network, by iteratively altering its internal architecture in response to the provided image and categorisation. This is done by presenting the neural network with the set of input images, and specifying the correct output condition that must be achieved.

The training process then modifies each of the hidden layers (starting with random weighting) until the overall network generates a transformation of the input layer values into an output value that corresponds to the correct category.

The network is trained until it has converged to a sufficient specificity. It is possible to "over train" a neural network, such that it can only categorise a frame to be recognised as a single frame, not the more general case that is needed for this application.

The subset of images used for testing has no overlap with those used for training, to ensure that there is sufficient variation between the two and ensure that the neural network is usable in the general case of different welds.

The testing phase measures the ability of the neural network to perform the categorisation by providing it with a series of images that are completely unconnected with the training set. The neural network then processes and categorises these images, and the categorisation is checked manually for accuracy. This testing accuracy is the primary performance matrix for neural networks.

Optimisation of the neural network was performed with the following settings

- Optimiser: Adaptive Moment Estimation (Adam)
- Learning rate: $1x10^{-5}$
- First moment estimate exponential decay rates: 0.9
- Second moment estimate exponential decay rates: 0.999

3.3.10 Specific trials

Four phases of weld trials were performed, each of which generated optimal and non-optimal welding conditions, and had affiliated training and testing regimes with associated accuracy matrices.

In the Phase 1 trials, 37 videos of welding were produced, with a range of different welding parameters, in order to generate both “acceptable” and “defective” weld samples. The welding parameters used are given in Table 3-2 with the intended weld condition given in Table 3-3.

Table 3-2: Welding parameter variations – Phase 1

Parameter set	Background Current (A)	Primary current (A)	Voltage (V)	Travel speed (mm/min)	Wire feed speed (mm/min)
1	58	175	11	85	700
2	67	200	11	85	1200
3	85	250	11	100	500
4	85	250	11	100	750
5	85	250	11	100	750

Table 3-3: List of welding trials performed – Phase 1

Filename	Bead position	Layer	Parameter set	Defect category
180710-100139-NAMRC	Root - centre	Root	1	Excessive cap height
180710-101652-NAMRC	Root - centre	Root	1	Excessive cap height
180710-103718-NAMRC	Root - centre	Root	1	Good
180710-110211-NAMRC	Root - right	Layer 2	2	Good
180710-110211-NAMRC	Root - right	Layer 2	2	Lack of sidewall fusion
180710-111739-NAMRC	Root - right	Layer 2	3	Good
180710-112453-NAMRC	Root - right	Layer 2	3	Good
180710-113029-NAMRC	Root - left	Layer 2	3	Good
180710-113537-NAMRC	Root - left	Layer 2	3	Good
180710-113953-NAMRC	Root - left	Layer 2	3	Good
180710-114048-NAMRC	Root - left	Layer 2	3	Good
180710-131537-NAMRC	Fill - left	Layer 3	3	Forgotten wire
180710-132703-NAMRC	Fill - left	Layer 3	3	Good
180710-133001-NAMRC	Fill - left	Layer 3	3	Good
180710-133502-NAMRC	Fill - right	Layer 3	3	Good
180710-133744-NAMRC	Fill - right	Layer 3	3	Good
180710-134052-NAMRC	Fill - right	Layer 3	3	Good
180710-134924-NAMRC	Fill - left	Layer 4	4	Lack of sidewall fusion
180710-135347-NAMRC	Fill - left	Layer 4	4	Good
180710-140026-NAMRC	Fill - left	Layer 4	4	Excessive sidewall fusion
180710-140827-NAMRC	Fill - right	Layer 4	4	Good
180710-141126-NAMRC	Fill - right	Layer 4	4	Good
180710-141126-NAMRC	Fill - right	Layer 4	4	Excessive sidewall fusion
180710-142407-NAMRC	Fill - left	Layer 5	5	Lack of sidewall fusion
180710-142407-NAMRC	Fill - left	Layer 5	5	Excessive arc length
180710-143228-NAMRC	Fill - left	Layer 5	5	Arc length too short
180710-144752-NAMRC	Fill - centre	Layer 5	5	Good
180710-152351-NAMRC	Fill - centre	Layer 5	5	Good
180710-153437-NAMRC	Fill - left	Layer 6	3	Forgotten wire
180710-153437-NAMRC	Fill - left	Layer 6	3	Lack of sidewall fusion
180710-153743-NAMRC	Fill - left	Layer 6	3	Arcing on sidewall
180711-093153-NAMRC	Fill - centre	Layer 7	3	Good
180711-093153-NAMRC	Fill - centre	Layer 7	3	Excessive current
180711-093846-NAMRC	Fill - centre	Layer 7	3	Good
180711-093846-NAMRC	Fill - centre	Layer 7	3	Insufficient current
180711-102904-NAMRC	Fill - left	Layer 8	3	Good
180711-103354-NAMRC	Fill - left	Layer 8	3	Excessive travel speed

The final weld sample produced is shown in Figure 3-10, with selected macro sections through the weld sample showing variations in the bead shape and presence/absence of defects given in Figure 3-11 to Figure 3-22.

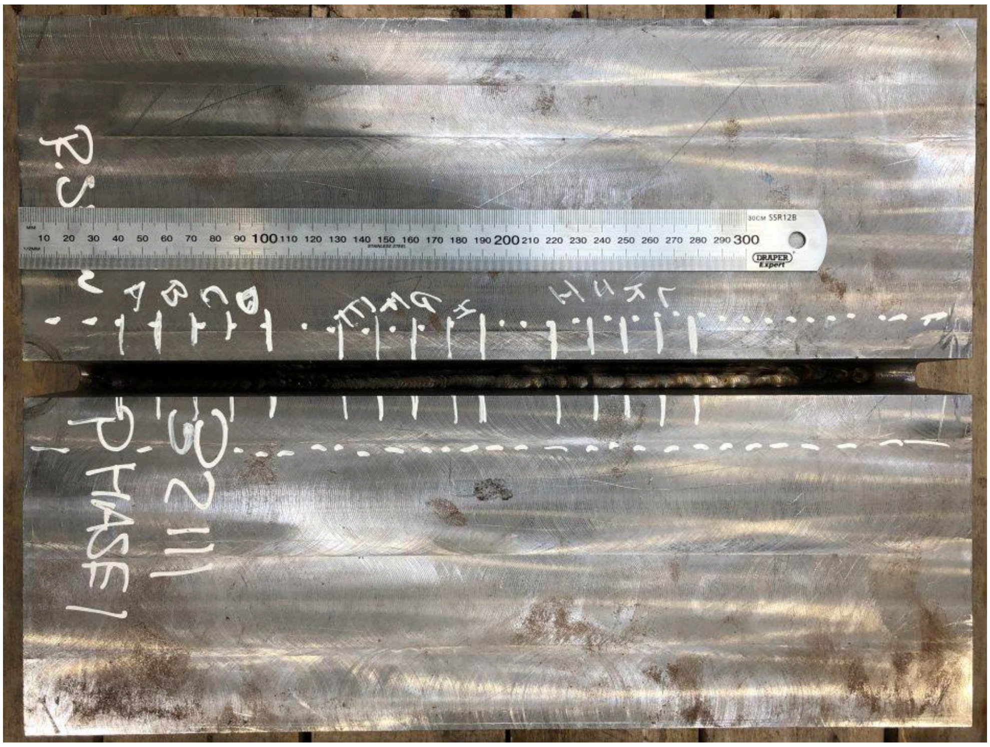

Figure 3-10: Phase 1 weld sample

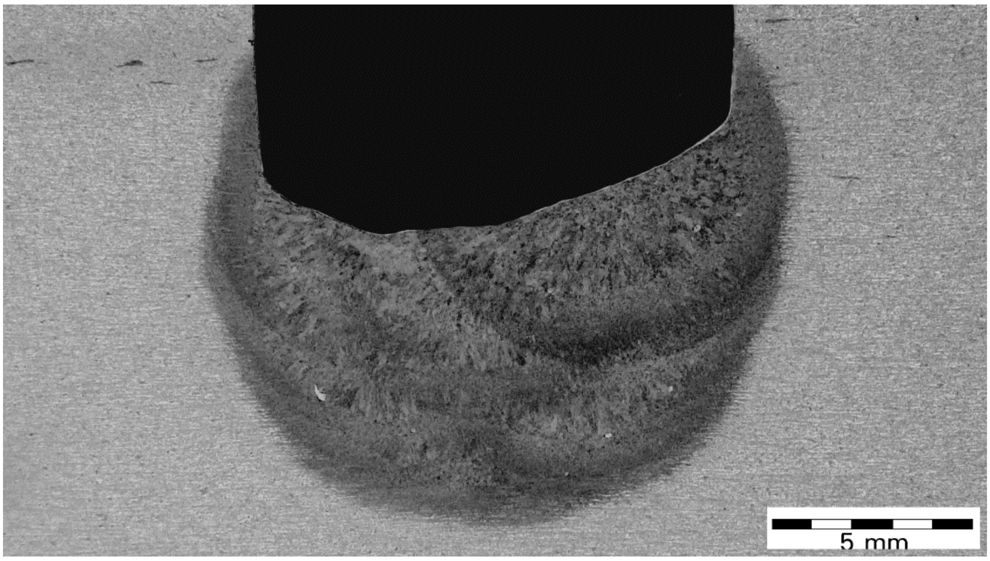

Figure 3-11: Macrograph from Phase 1 plate, position A.

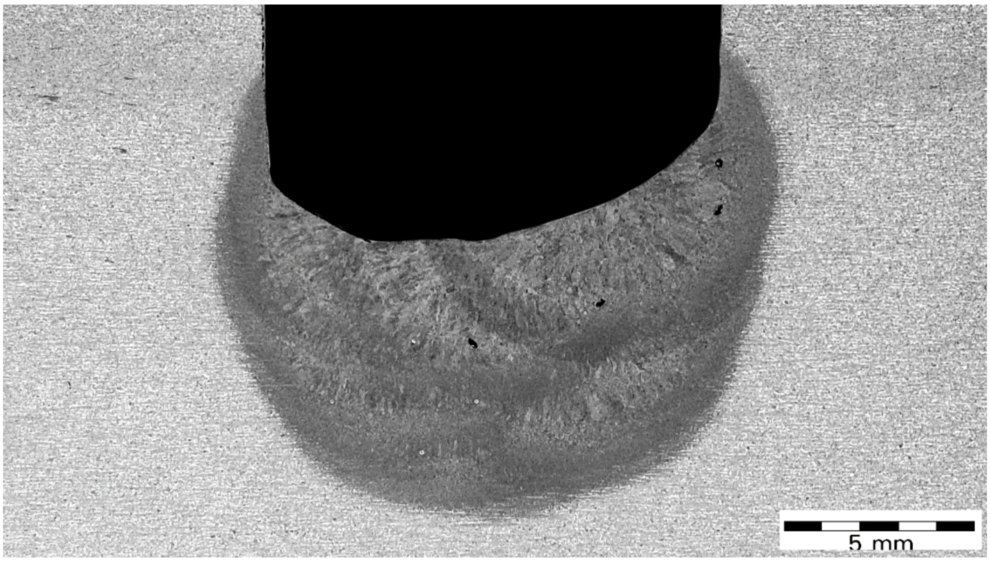

Figure 3-12: Macrograph from Phase 1 plate, position B showing lack of fusion defects.

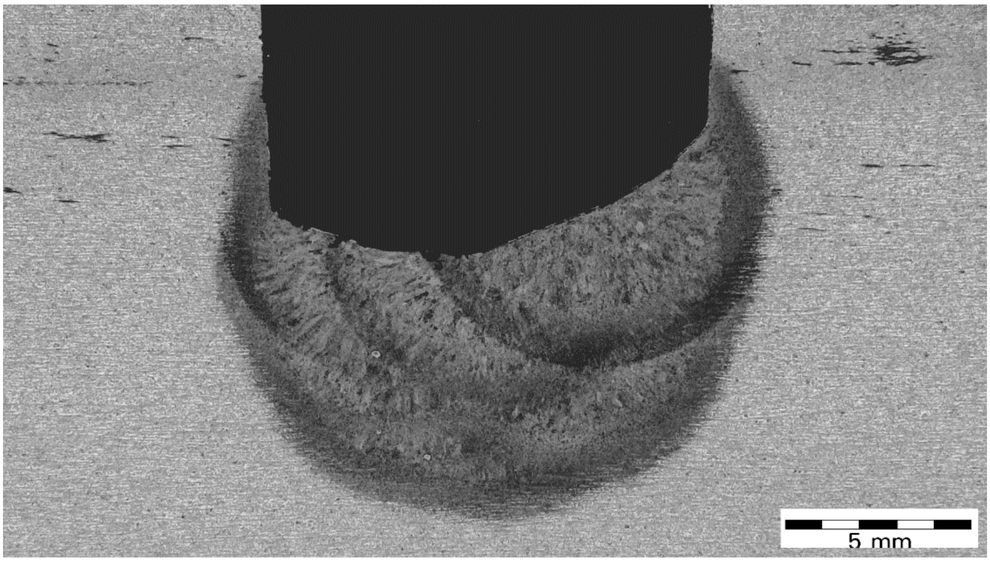

Figure 3-13: Macrograph from Phase 1 plate, position C.

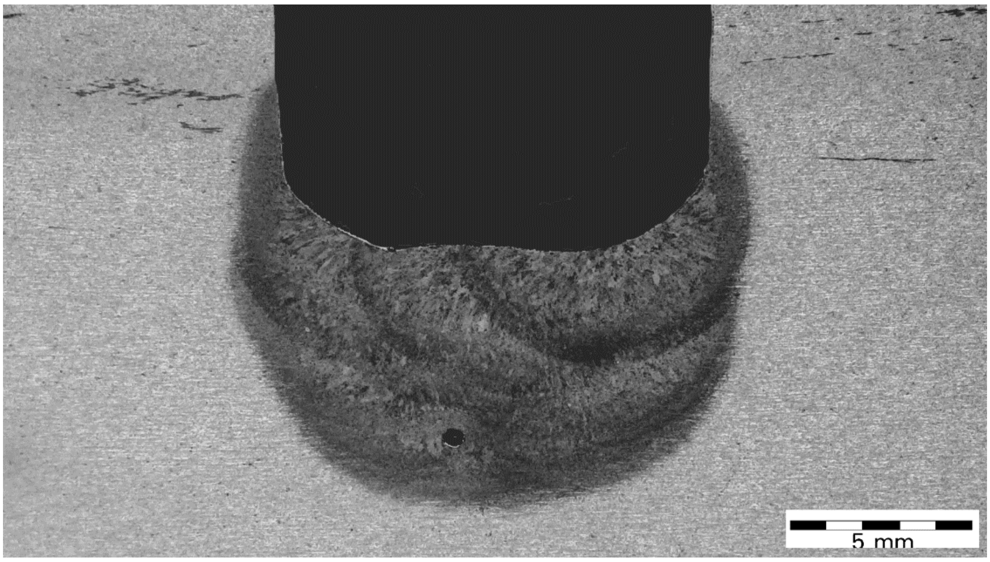

Figure 3-14: Macrograph from Phase 1 plate, position D showing porosity.

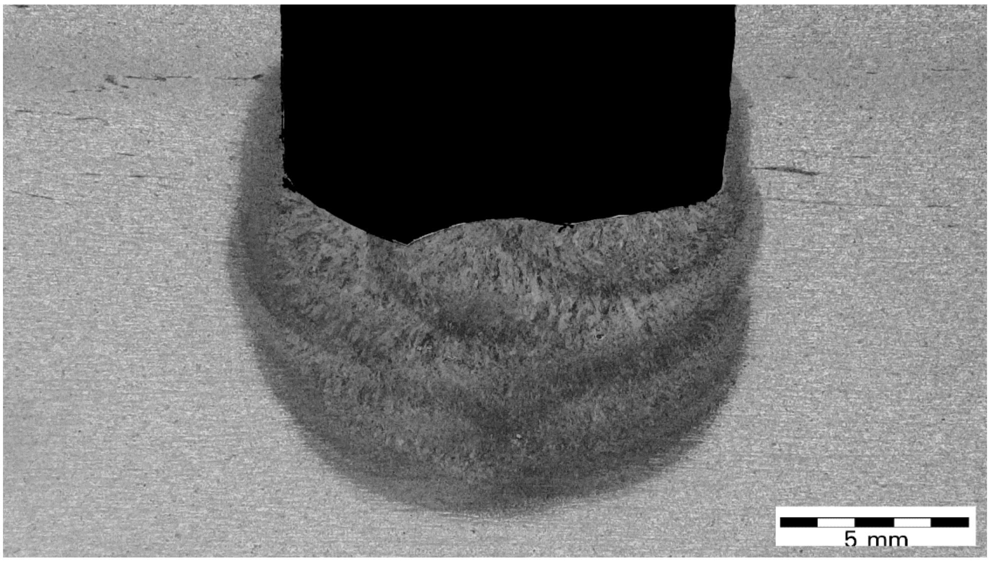

Figure 3-15: Macrograph from Phase 1 plate, position E.

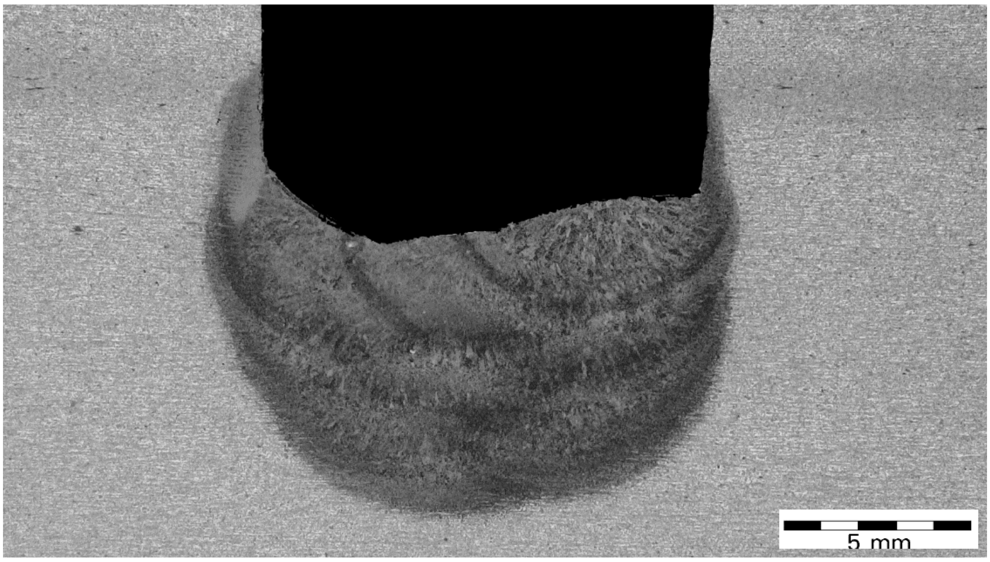

Figure 3-16: Macrograph from Phase 1 plate, position F.

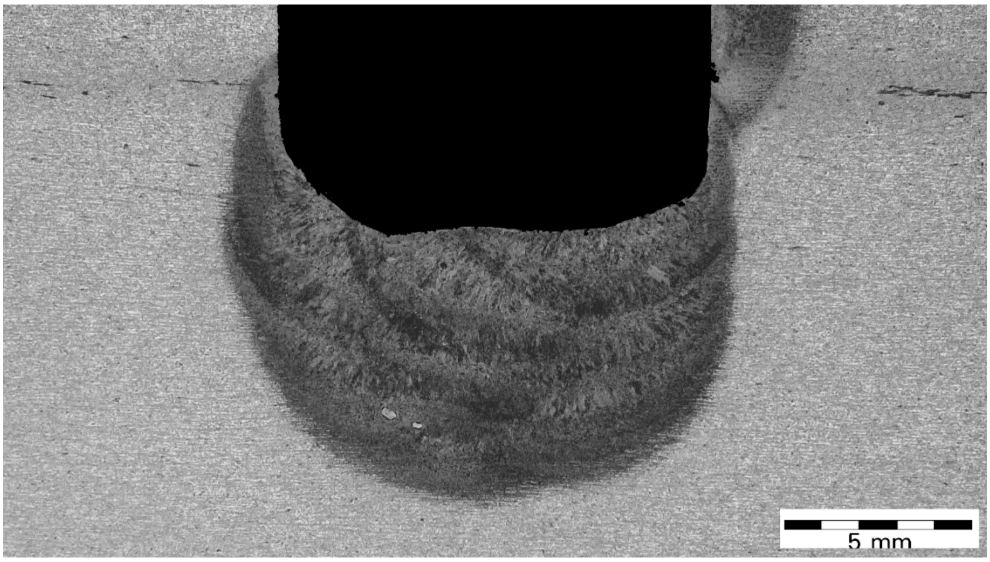

Figure 3-17: Macrograph from Phase 1 plate, position G.

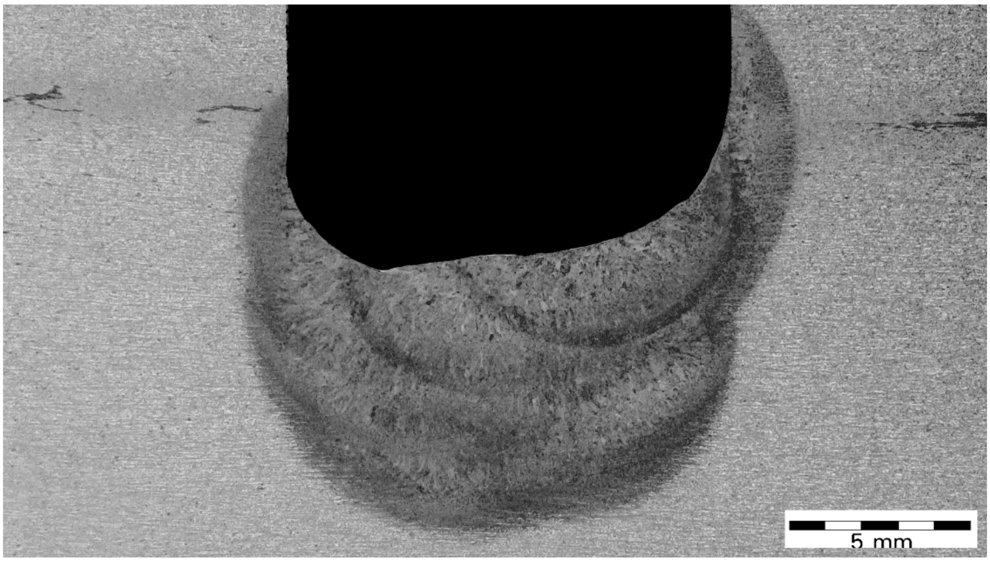

Figure 3-18: Macrograph from Phase 1 plate, position H.

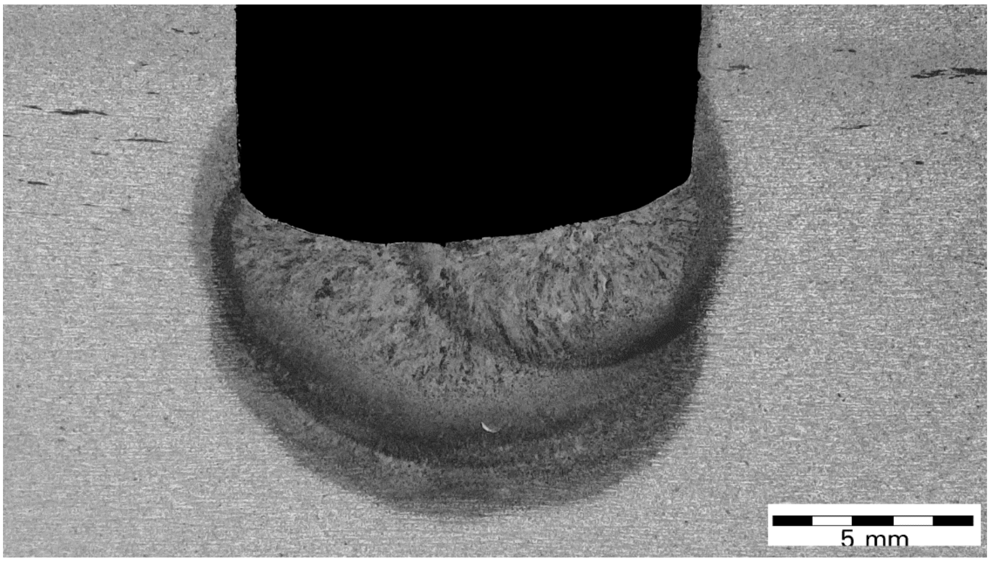

Figure 3-19: Macrograph from Phase 1 plate, position I.

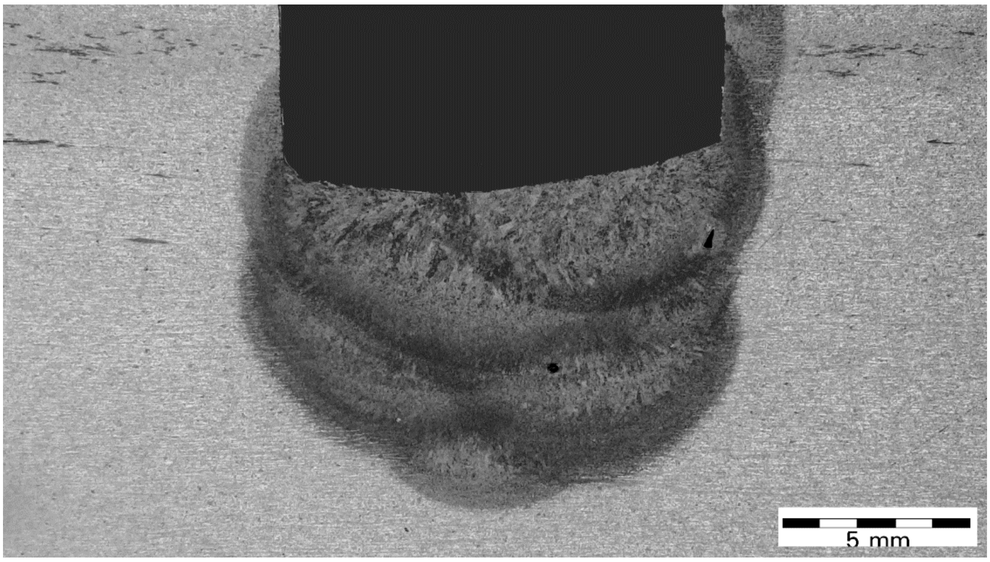

Figure 3-20: Macrograph from Phase 1 plate, position J showing lack of sidewall and inter-run fusion.

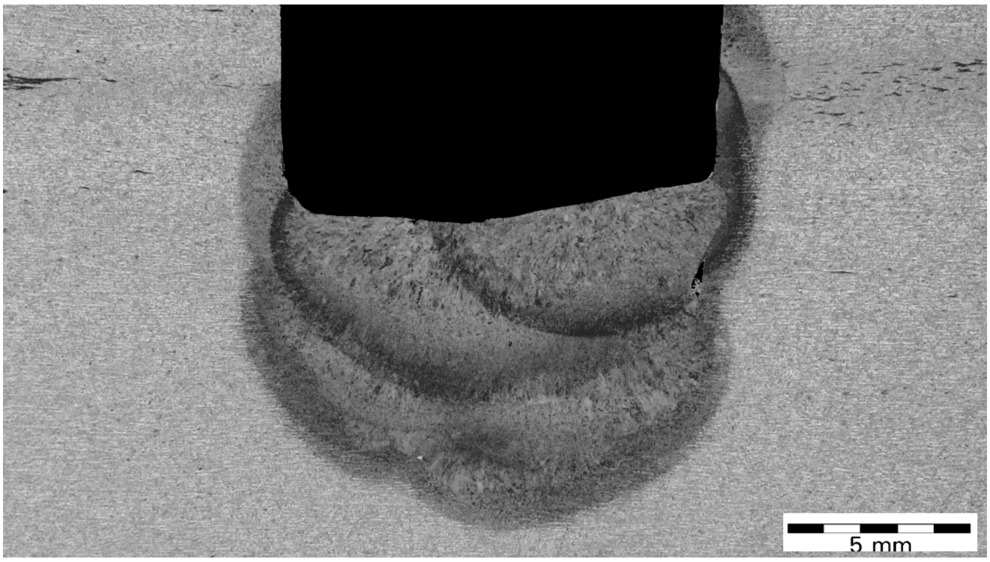

Figure 3-21: Macrograph from Phase 1 plate, position K showing lack of sidewall fusion.

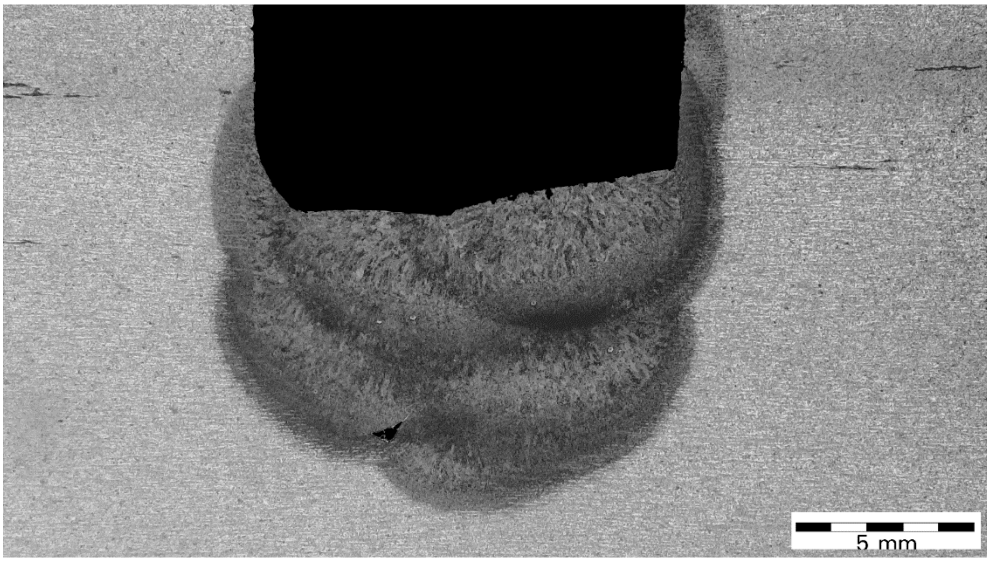

Figure 3-22: Macrograph from Phase 1 plate, position L showing cap porosity and lack of inter-run fusion.

The training and test datasets of frames recorded during this process are given in Table 3-4, and the output accuracy recorded is given in Table 3-5. Only the defect types for which there were sufficient numbers to test are shown. The categorisation of the input images is given in the columns for each row. As an example to aid comprehension of Table 3-5, 73 of the "good weld" images were incorrectly categorised as "excessive arc length", shown in red.

Table 3-4: The Phase 1 training and testing image datasets

Category	Number of images in training dataset	Number of images in testing dataset	Number of images total
Good weld	13187	9456	22643
Excessive arc length	1441	0	1441
Insufficient arc length	70	0	70
Excessive cap height	2305	2992	5297
Excessive current	1409	0	1409
Insufficient current	150	0	150
Insufficient filler wire addition	1161	464	1625
Arcing onto sidewall	1065	0	1065
Excessive sidewall fusion	1493	1070	2563
Insufficient sidewall fusion	3271	523	3794
Excessive travel speed	124	0	124

Table 3-5: Phase 1 accuracy matrix

	Output of neural network										
Input image	Good weld	Excessive arc length	Insufficient arc length	Excessive cap height	Excessive current	Insufficient current	Insufficient filler wire addition	Arcing onto sidewall	Excessive sidewall fusion	Insufficient sidewall fusion	Excessive travel speed
Good weld	9104	73	0	0	0	0	0	80	0	157	42
Excessive cap height	2004	0	1	0	0	0	0	0	0	735	252
Insufficient filler wire addition	0	2	0	0	0	0	0	0	0	462	0
Excessive sidewall fusion	1070	0	0	0	0	0	0	0	0	0	0
Insufficient sidewall fusion	0	0	0	0	0	0	0	0	0	517	6

During the accuracy assessment, one of the major difficulties discerned was the uneven spread of training images, as this can bias the neural network to favour certain responses if it has been forwarded a larger number of a given category. As such, each further phase was progressed with an attempt to balance the uniformity in the training dataset, with an equal number of frames for each category.

In the Phase 2 trials, 71 videos of welding were produced, with a range of different welding parameters, in order to generate both "acceptable" and "defective" weld samples. The welding parameters used are given in Table 3-6, with the intended weld condition given in Table 3-7.

Table 3-6: Welding parameter variations – Phase 2

Parameter set	Background Current (A)	Primary current (A)	Voltage (V)	Travel speed (mm/min)	Wire feed speed (mm/min)
1	58	175	11	85	700
2	67	200	11	85	1200
3	85	250	11	100	500
4	85	250	11	100	750
5	85	250	11	100	750
6	117	350	11	100	750
7	85	250	11	200	750
8	33	100	11	100	750
9	85	250	17.5	100	750
10	85	250	11	100	0
11	85	250	13.5	100	750
12	100	300	11	100	750
13	85	250	12	100	750
14	40	120	11	100	750
15	60	180	11	100	750
16	73	220	11	100	750
17	85	250	11	140	750
18	85	250	11	160	750
19	85	250	11	180	750
20	117	350	11	140	750
21	85	250	11	100	1000
22	100	300	11	100	1000
23	100	300	11	100	1200
24	100	300	11	100	1400
25	117	350	12	100	1400
26	117	350	12.5	100	2000
27	117	350	13	100	2500
28	117	350	13	125	2500
29	117	350	13	200	2500
30	67	200	13	200	2500
31	117	350	13	200	0
32	117	350	13	100	0
33	67	200	11	100	750
34	50	150	11	100	750
35	67	200	11	100	0
36	85	250	11.5	150	750
37	85	250	11.5	100	750
38	85	250	11.5	300	750
39	85	250	11.5	350	0
40	117	350	11.5	350	0
41	117	350	12.5	100	750
42	117	350	13	100	2000

Table 3-7: List of welding trials performed – Phase 2

Filename	Bead position	Layer	Parameter set	Defect category
180917-141525-NAMRC	Root - centre	Root	1	Excessive cap height
180917-143322-NAMRC	Root – left	Root	1	Lack of sidewall fusion
180917-144007-NAMRC	Root - right	Root	1	Insufficient current
180917-145133-NAMRC	Fill – centre	Layer 2	5	Good
180917-150627-NAMRC	Fill – left	Layer 2	5	Insufficient arc length
180917-152003-NAMRC	Fill – right	Layer 2	6	Good
180918-084130-NAMRC	Fill – centre	Layer 3	7	Excessive travel speed
180918-084849-NAMRC	Fill – left	Layer 3	7	Excessive travel speed
180918-085351-NAMRC	Fill – right	Layer 3	7	Excessive travel speed
180918-090024-NAMRC	Fill – centre	Layer 4	6	Excessive current
180918-090730-NAMRC	Fill – left	Layer 4	6	Excessive current
180918-092358-NAMRC	Fill – right	Layer 4	6	Excessive current
180918-101919-NAMRC	Fill – centre	Layer 5	8	Insufficient current
180918-102441-NAMRC	Fill – left	Layer 5	5	Sidewall arcing
180918-103140-NAMRC	Fill – right	Layer 5	5	Sidewall arcing
180918-103849-NAMRC	Fill – centre	Layer 6	6	Excessive current
180918-131524-NAMRC	Fill – right	Layer 6	6	Excessive current
180918-132110-NAMRC	Fill – centre	Layer 6	9	Excessive arc length
180918-132740-NAMRC	Fill – centre	Layer 6	10	No wire – clean-up
180918-133329-NAMRC	Fill – centre	Layer 7	11	Excessive arc length
180918-133825-NAMRC	Fill – left	Layer 7	12	Good
180918-134940-NAMRC	Fill – right	Layer 7	13	Excessive arc length
180918-135502-NAMRC	Fill – centre	Layer 7	14	Insufficient current
180918-135940-NAMRC	Fill – centre	Layer 8	6	Excessive current
180918-140852-NAMRC	Fill – left	Layer 8	15	Insufficient current
180918-142444-NAMRC	Fill – left	Layer 8	12	Good – clean-up
180918-142943-NAMRC	Fill – right	Layer 8	16	Insufficient current
180918-143816-NAMRC	Fill – left	Layer 8	12	Good – clean-up
180918-144335-NAMRC	Fill – centre	Layer 9	17	Excessive travel speed
180918-144714-NAMRC	Fill – left	Layer 9	18	Excessive travel speed

Filename	Bead position	Layer	Parameter set	Defect category
180918-145138-NAMRC	Fill – left	Layer 9	12	Good – clean-up
180918-145701-NAMRC	Fill – right	Layer 9	19	Excessive travel speed
180919-083802-NAMRC	Fill – centre	Layer 10	19	Excessive travel speed
180919-084350-NAMRC	Fill – right	Layer 10	18	Excessive travel speed
180919-084913-NAMRC	Fill – left	Layer 10	19	Excessive travel speed
180919-090218-NAMRC	Fill – centre	Layer 10	20	Excessive current
180919-090703-NAMRC	Fill – centre	Layer 11	21	Good
180919-092105-NAMRC	Fill - right	Layer 11	22	Good
180919-092928-NAMRC	Fill – left	Layer 11	23	Lack of sidewall fusion
180919-101635-NAMRC	Fill – right	Layer 11	24	Good
180919-103858-NAMRC	Fill - left	Layer 11	25	Good
180919-104726-NAMRC	Fill - right	Layer 12	26	Good
180919-105531-NAMRC	Fill – left	Layer 12	27	Good
180919-110459-NAMRC	Fill – right	Layer 12	28	Good
180919-111125-NAMRC	Fill – left	Layer 12	29	Good
180919-111810-NAMRC	Fill – centre	Layer 12	30	Insufficient current / Excessive travel speed
180919-112418-NAMRC	Fill – centre	Layer 13	31	Irregular
180919-113522-NAMRC	Fill – centre	Layer 13	32	Irregular
180919-114652-NAMRC	Fill – left	Layer 13	33	Good
180919-130718-NAMRC	Fill – right	Layer 13	34	Insufficient current / Excessive sidewall fusion
180919-131206-NAMRC	Fill – right	Layer 13	34	Insufficient sidewall fusion
180919-131953-NAMRC	Fill – right	Layer 13	35	No wire – clean-up
180919-132410-NAMRC	Fill – centre	Layer 14	34	Excessive cap height
180919-133019-NAMRC	Fill – right	Layer 14	34	Insufficient arc length
180919-134826-NAMRC	Fill – left	Layer 14	36	Good
180919-135147-NAMRC	Fill – left	Layer 14	37	Good
180919-135429-NAMRC	Fill – left	Layer 14	38	Excessive travel speed
180919-135741-NAMRC	Fill – right	Layer 14	38	Excessive travel speed
180919-140036-NAMRC	Fill – centre	Layer 15	39	Excessive travel speed / No wire
180919-140347-NAMRC	Fill – centre	Layer 15	40	Excessive travel speed / No wire
180919-140704-NAMRC	Fill – centre	Layer 15	41	Excessive current
180919-141829-NAMRC	Fill – left	Layer 15	42	Excessive current
180919-142328-NAMRC	Fill – right	Layer 15	42	Excessive current

The final weld sample produced is shown in Figure 3-23, with selected macro sections through the weld sample showing variations in the bead shape and presence/absence of defects given in Figure 3-24 to Figure 3-29.

Figure 3-23: Phase 2 weld sample.

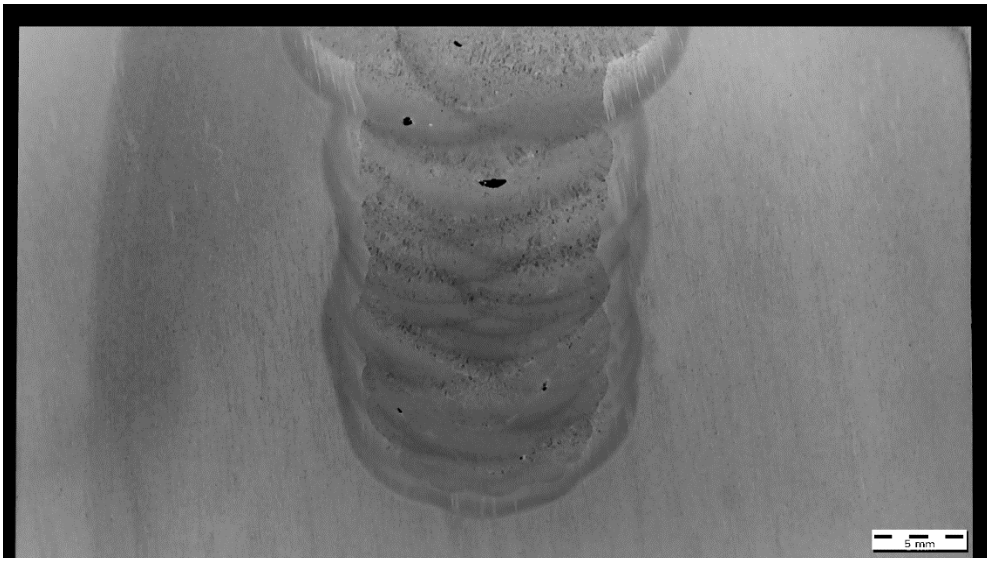

Figure 3-24: Macrograph from Phase 2 plate, position A showing porosity and lack of inter-run fusion.

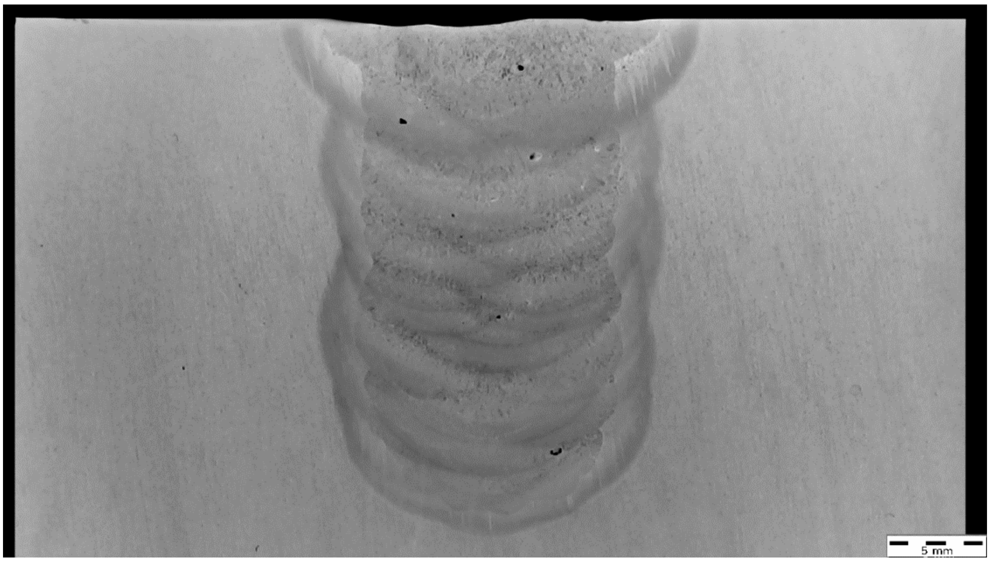

Figure 3-25: Macrograph from Phase 2 plate, position B showing porosity and lack of inter-run fusion.

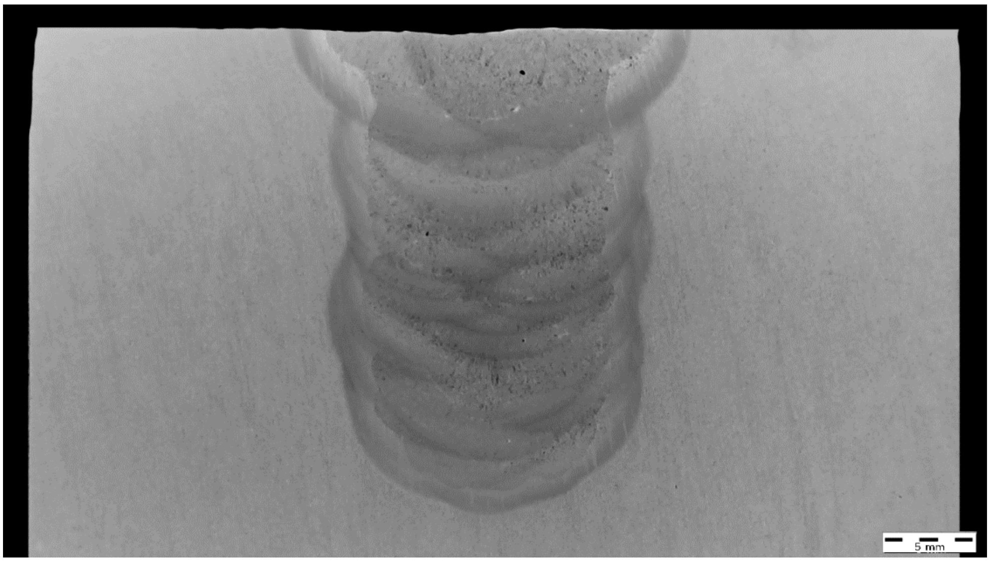

Figure 3-26: Macrograph from Phase 2 plate, position C showing porosity.

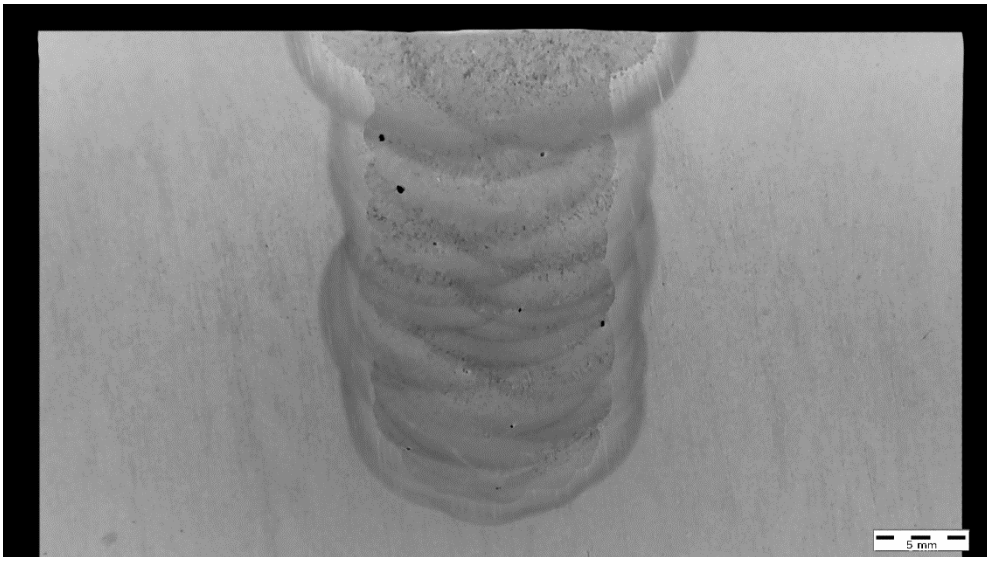

Figure 3-27: Macrograph from Phase 2 plate, position D showing porosity.

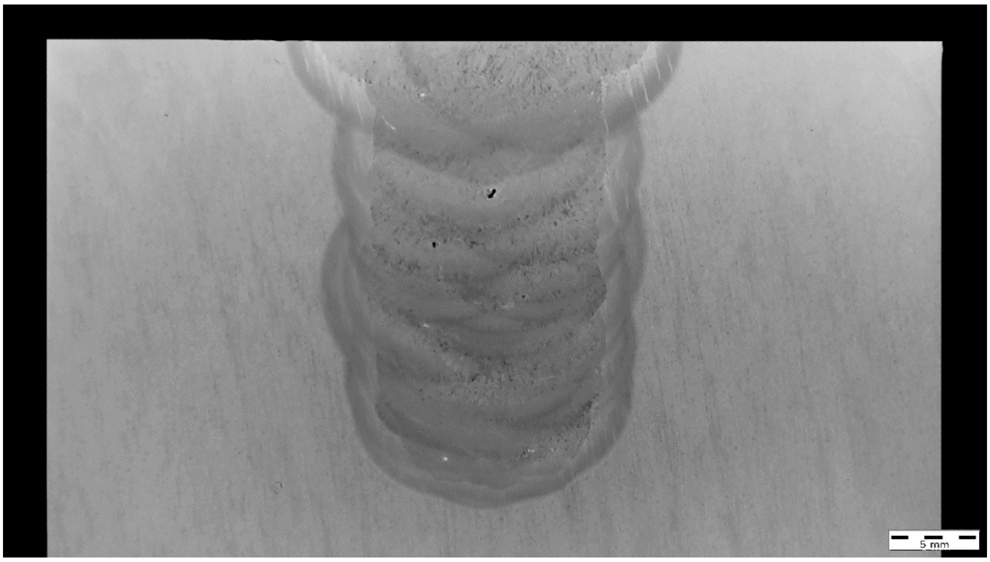

Figure 3-28: Macrograph from Phase 2 plate, position E showing porosity.

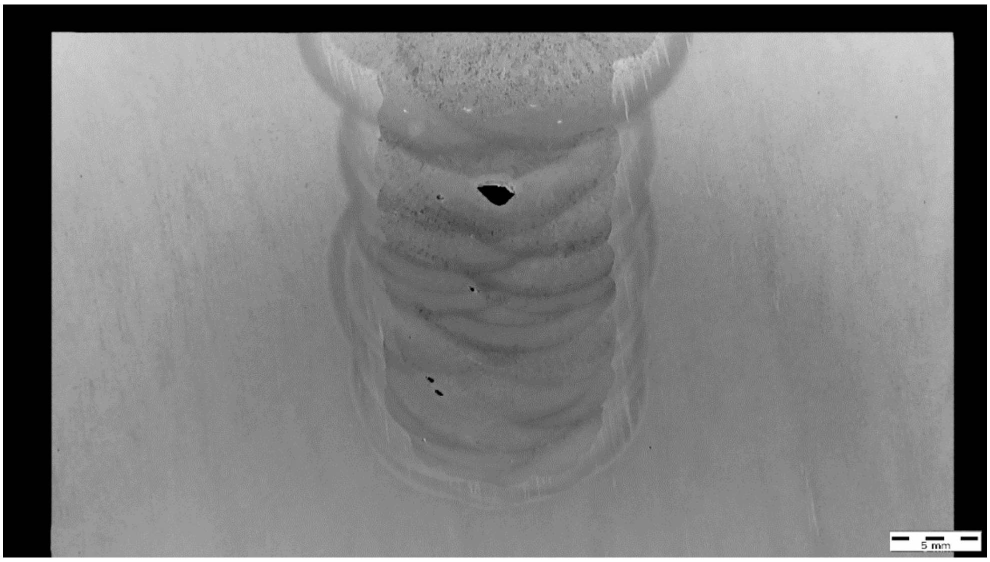

Figure 3-29: Macrograph from Phase 2 plate, position F showing gross porosity.

The training and test datasets of frames recorded during this process are given in Table 3-8, and the output accuracy recorded is given in Table 3-9.

Table 3-8: The Phase 2 training and testing image datasets

Ref. number	Weld type	No. samples	% of max
1	Good	10689	90
2	Excessive arc length	11484	97
3	Insufficient arc length	6023	51
4	Excessive cap height	11826	99
5	Excessive current	10352	87
6	Insufficient current	11896	100
7	No wire	1625	14
8	Sidewall arcing	4948	42
9	Excessive sidewall fusion	8137	68
10	Insufficient sidewall fusion	9817	83
Total		86797	

Table 3-9: Phase 2 accuracy matrix

	Output of neural network										
Input image	Good weld	Excessive arc length	Insufficient arc length	Excessive cap height	Excessive current	Insufficient current	Insufficient filler wire addition	Sidewall arcing	Excessive sidewall fusion	Insufficient sidewall fusion	Accuracy (%)
Good weld	2891	19	30	230	164	12	217	0	1	126	78
Excessive arc length	0	3188	0		0	96	0	0	0	0	97
Insufficient arc length	904	571	1	29	360	43	0	0	0	39	~0
Excessive cap height	22	0	0	2963	4	3	0	0	0	0	99
Excessive current	36	299	26	0	1221	41	3	31	0	995	46
Insufficient current	32	545	3	0	0	1450	0	7	0	2	71
Insufficient filler wire addition	0	1	0	58	0	0	0	0	26	379	~0
Sidewall arcing	198	220	9	37	0	63	0	3	108	327	~0
Excessive sidewall fusion	399	0	0	0	7	334	54	0	276	0	26
Insufficient sidewall fusion	293	11	0	879	0	292	0	0	245	459	21

As seen in Table 3-9 compared with Table 3-5, additional improvements were made in the accuracy of the predictive model, but the system is not yet consistently accurate (e.g. all categorisations 80% accurate) for all defect types.

Certain defect types are location-dependent, meaning that they will have a different appearance on different sides of the weld bead, e.g. the lack of sidewall fusion. For these trials, the neural network does not have the additional context information that is available to a welding operator that a weld bead is located on the left or right of a component, and what influence that should have on the bead appearance. As such, it is likely that additional analysis and segregation with context clues will improve the accuracy for these specific defects.

In the Phase 3 trials, 28 videos of welding were produced, with a range of different welding parameters, in order to generate both “acceptable” and “defective” weld samples. The welding parameters used are given in Table 3-10, with the intended weld condition given in Table 3-11.

Table 3-10: Welding parameter variations – Phase 3

Parameter set	Background Current (A)	Primary current (A)	Voltage (V)	Travel speed (mm/min)	Wire feed speed (mm/min)
1	78	235	10.5	70	600
2	95	285	11.2	70	1200
3	111	335	11.2	70	1600
4	111	335	11.2	70	3000
5	111	250	11.2	70	1600
6	111	350	11.2	70	3000
7	111	335	11.2	70	0
8	111	335	10.2	70	1600

Table 3-11: List of welding trials performed – Phase 3

Filename	Bead position	Layer	Parameter set	Defect category
190221-090201-NAMRC	Root - centre	Root	1	Good
190221-090458-NAMRC	Root – centre	Root	1	Good
190221-093046-NAMRC	Root – left	Root	2	Good
190221-103724-NAMRC	Root – right	Root	2	Good
190221-105423-NAMRC	Root – right	Root	2	No wire
190221-110933-NAMRC	Fill – left	Layer 1	3	No wire
190221-111922-NAMRC	Fill – left	Layer 1	3	Good
190221-113429-NAMRC	Fill – right	Layer 1	3	Excessive sidewall fusion
190221-114934-NAMRC	Fill – right	Layer 1	3	Good
190221-132301-NAMRC	Fill – left	Layer 2	3	Good
190221-133708-NAMRC	Fill – right	Layer 2	4	Excessive cap height
190221-135510-NAMRC	Fill – centre	Layer 2	4	Excessive cap height
190221-141520-NAMRC	Fill – left	Layer 2	3	Insufficient sidewall fusion
190221-144322-NAMRC	Fill – left	Layer 2	3	Good
190221-145536-NAMRC	Fill – left	Layer 3	3	Good
190222-084256-NAMRC	Fill – right	Layer 3	3	Excessive sidewall fusion
190222-090303-NAMRC	Fill – right	Layer 3	3	Excessive sidewall fusion
190222-091356-NAMRC	Fill – left	Layer 3	3	Excessive sidewall fusion
190222-093553-NAMRC	Fill – left	Layer 3	3	Excessive sidewall fusion
190222-102013-NAMRC	Fill – right	Layer 4	3	Excessive sidewall fusion
190222-103904-NAMRC	Fill – right	Layer 4	5	Sidewall arcing
190222-105132-NAMRC	Fill – left	Layer 4	5	Sidewall arcing
190222-105713-NAMRC	Fill – left	Layer 4	5	Sidewall arcing
190222-111059-NAMRC	Fill – centre	Layer 5	6	Excessive cap height
190222-113827-NAMRC	Fill – right	Layer 5	7	No wire
190222-114641-NAMRC	Fill – left	Layer 5	7	No wire/Excessive sidewall fusion
190222-115723-NAMRC	Fill – left	Layer 5	8	Insufficient arc length
190222-120003-NAMRC	Fill – left	Layer 5	8	Insufficient arc length

Selected macro sections through the weld sample are given in Figure 3-30 and Figure 3-31.

Figure 3-30: Macrograph from Phase 3 plate, position A.

Figure 3-31: Macrograph from Phase 3 plate, position B.

In the Phase 4 trials, 176 videos of welding were produced. It was not possible to analyse all of these videos during the project, but a subset were examined. Due to the large quantity of videos, unlike previous phases, welding parameters and trials are not listed.

Selected macro sections through the weld sample given in Figure 3-32 and Figure 3-33.

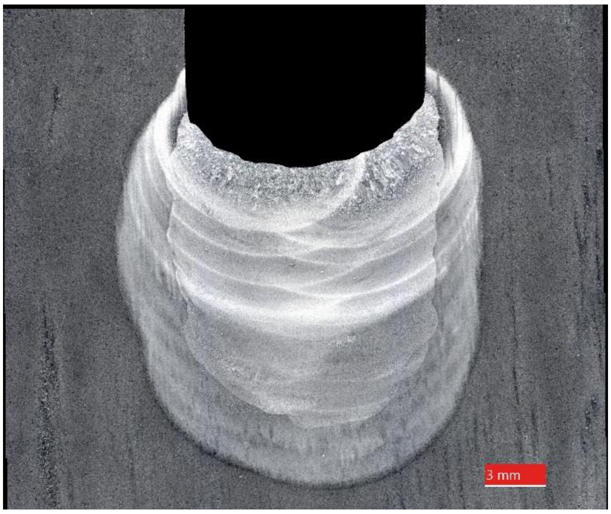

Figure 3-32: Macrograph from Phase 4 plate, position 1.

Figure 3-33: Macrograph from Phase 4 plate, position 2 showing porosity and excessive sidewall fusion (undercut).

The output accuracy recorded from the analysis of Phases 3 and 4 is given in Table 3-12.

Table 3-12: Phases 3 and 4 accuracy matrix

	Output of neural network								
Input image	Good weld	Excessive arc length	Excessive cap height	Excessive current	Insufficient current	Sidewall arcing	Excessive sidewall fusion	Insufficient sidewall fusion	Accuracy (%)
Good weld	3418	43	3	19	3	0	128	76	92
Excessive arc length	21	2559	0	0	586	116	0	2	78
Excessive cap height	190	52	2662	0	1	0	0	87	89
Excessive current	227	4	1	1137	23	119	0	1141	43
Insufficient current	53	464	0	0	2522	0	0	0	83
Sidewall arcing	223	25	0	0	1	4	355	457	~0
Excessive sidewall fusion	474	7	0	10	21	0	558	0	52
Insufficient sidewall fusion	2017	47	1	0	92	0	23	0	0

As seen in Table 3-12 compared with Table 3-9, additional improvements were made in the accuracy of some of the categories, but this was at the cost of accuracy in others. Overall accuracy was improved, but there is evidently a risk of introducing new bias to a relatively uniform data set, and the neural network model is obviously not yet stable. Analysis of the available data set will continue, and the significant increase in input files will allow further granularity (e.g. location-dependency) which will likely improve the accuracy further.

3.4 Ongoing work

An additional two phases of weld trials have been performed, and analysis of the videos collected during that welding is ongoing. In the Phase 3 trials, 29 welds were performed and in the Phase 4 trials, which used the fully integrated data collection system, 166 welds were performed.

More detailed analysis of the recorded videos in Phase 3 and Phase 4 is being applied relative to Phases 1 and 2, to attempt to improve the sensitivity of the analysis process to the different sides of the welded groove.

Time-based analysis of the defect categorisation is ongoing, which is looking at the manner in which the categorisation varies through frames in sequence, to determine if there is improved accuracy when the frames are considered in groups rather than isolation. This will determine the final response time of the analysis system. For example, if the single frame categorisation accuracy is 80%, the chance of a false positive given three frames is <1%. Therefore the response time can be considered to be three frames. Given a 25-50 Hz sampling frequency, this will result in a quicker response relative to an operator.

Examples of the time-based breakdown of frame categorisation are shown in Figure 3-34 and Figure 3-35. A value of "1" indicates that the neural network correctly categorised the frame, and a value of "0" indicates that the neural network incorrectly categorised the frame. Clusters of different categories can be observed throughout the video breakdown, and these need to be manually correlated with the visual data, in order to improve the accuracy of the neural network.

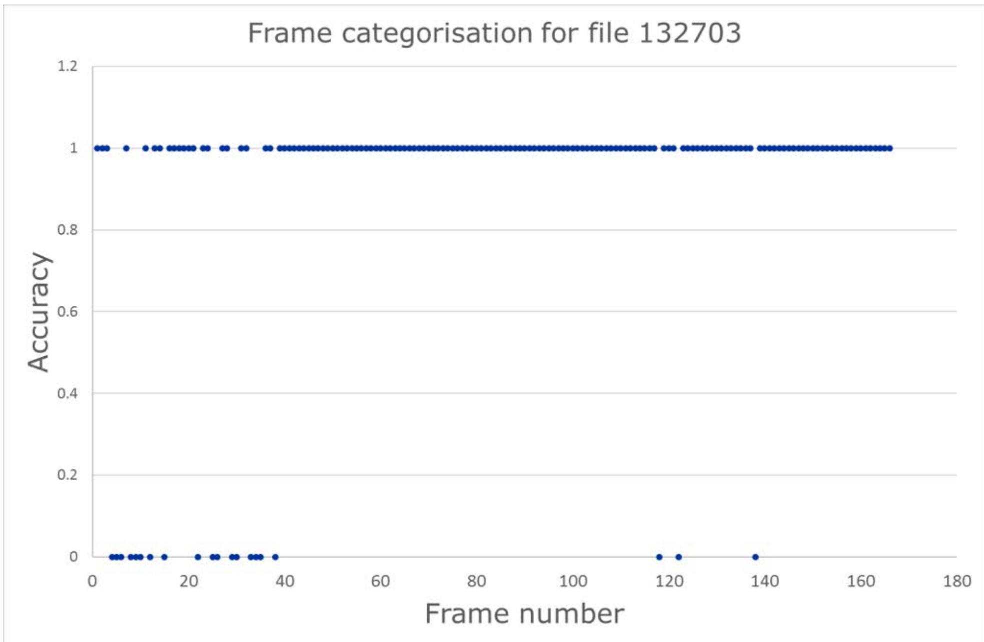

Figure 3-34: Time-based analysis for file 132703.

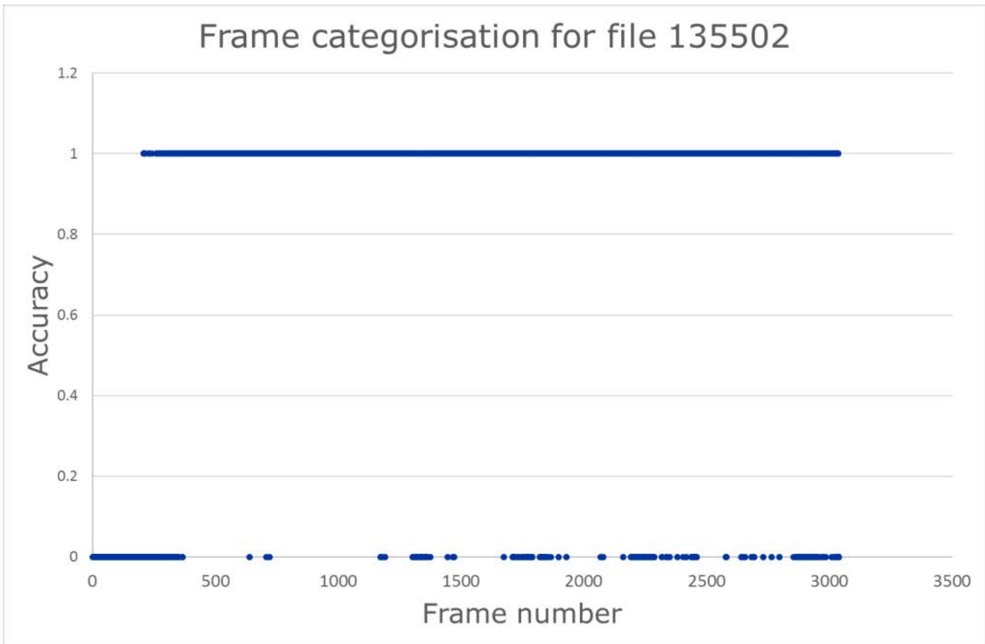

Figure 3-35: Time-based analysis for file 135502.

Analysis is also being performed to determine what the minimum number of required frames is for each particular categorisation type, as the accuracy is not consistent for all categories. As such, a relatively complex lookup table is required to specify the minimum number of detectable incidents before the system interrupts the welding process.

3.5 Alternative approaches

There are a number of possible changes to the experimental approach that may improve the speed of application for future investigations into the use of the visual analysis system.

The system has been applied to a welding process and shown some success in accurately detecting the presence or absence of defects. The visual analysis components have been integrated into a monitoring system that takes in multiple information streams (audio analysis, parametric analysis etc) and time synchronises all of this data. However, the current visual analysis setup requires sending information outside of the overall windows environment in order to process the images through the Unix-based neural network.

The Unix approach was taken due to the particular technical expertise of the team involved in assembling the system, however it would be preferable to have the entire workflow within a single environment (likely Windows-based). This would enable quicker data collection, neural network analysis and potential feedback, which would improve the response time of the overall system.

This would also allow better integration of the visual data with all of the other information streams. There are certain defect types, which have generally shown the lowest accuracy for detection. These are ones which contain additional variations in the image beyond that expected to correlate with the presence or absence of defects.

For example, sidewall arcing, lack of sidewall fusion, and excessive sidewall fusion, all contain additional visual information, which is associated with the sidewall of the joint preparation. Figure 3-36 shows two images, both of which are allocated to a single "defect" category, but which contain contextual information that a human can readily parse, but which is not easily comprehended by the neural network system. Namely, that the sidewall is either on the left or right of the image. Visual analysis of these images can be enhanced by the operator increasing the granularity of the categorisation (e.g. into "defect (left)" and "defect (right)", however it would be preferable for this to be built into the automated system itself.

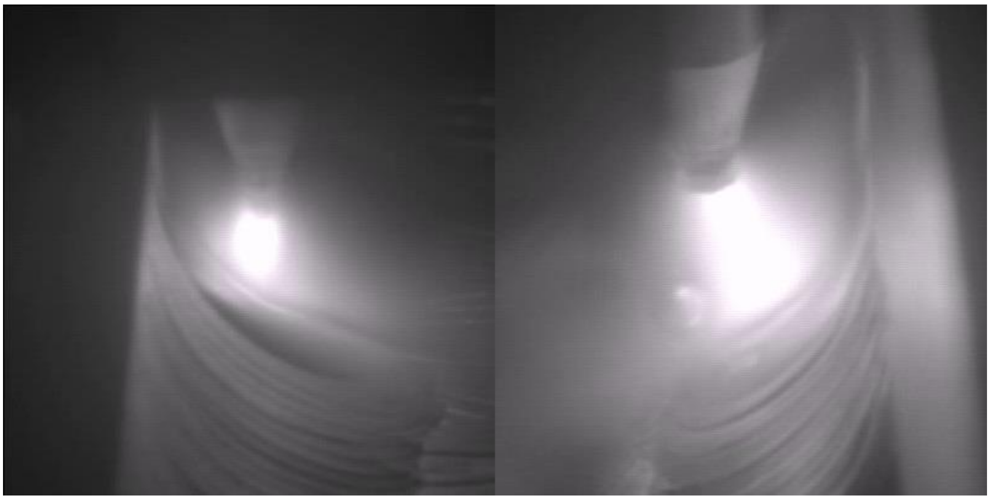

Figure 3-36: Comparison of different images assigned to single category.

This could be done by developing integration as a starting point, rather than integrating the multiple streams after they have been individually developed. This could either be in the form of adding additional data points to the existing neural network or by using a machine-learning algorithm, that considers all of the different information streams simultaneously. This will require developing a consistent data standard to be shared between each of the streams, and correlation of input signals to a given set of pre-defined weld quality states (e.g. optimal or defect).

Another possible approach to develop the system requires already existing welding data. The development route has relied upon producing intentional defects or altering the welding process in order to introduce non-optimal welding conditions, which then are recorded for visual analysis. While these will be relatively similar to non-intentional defects, it may be preferable to start with an existing set of visual welding data from a production welding environment which is already correlated with NDE data and can be used for training.

There is likely to be a very large amount of visual data available in industry, and making use of this would potentially shortcut a large amount of the development process and the need to generate artificial defects, which may not precisely match "real world" defects. Use of this existing data will also introduce the technology to industrial partners who may be able to facilitate uptake of the technology.

4 End TRL and MRL level

4.1 Potential industrial impact

The vision system has been assembled and used for Narrow Groove GTAW, and shows promise for the analysis and categorisation for a range of different non-optimal welding conditions. The system is not currently capable of categorising all of the frames into their intended conditions, at what might be considered an "acceptable industrial level" of accuracy, e.g. 99%. However, the principle has been demonstrated, and improvements observed during the phases have indicated that the system will continue to increase in accuracy, so consideration can be given to a system that will observe defects in-process.

For Narrow Groove GTAW, the ability of the welding equipment to detect defects is a considerable benefit, if this allows reduction of repair procedures. A repair procedure will involve ancillary inspection, grinding, manual repair, specialised expertise and consultancy cost, and a number of support roles. A simple repair can cost a minimum of £10-20k in external costs. The cost and time saving affiliated with this is significant, and would also lead to components "right first time". There are auxiliary savings related to the development and qualification of the repair procedures, as well as the requisite training of a manual welder and machinist.

Given that certain defects specified for categorisation are dependent on the weld pool placement, these are correlated with the typical actions of a welding operator who adjusts the process during welding. This can, for example, by movement of the tungsten electrode perpendicular to the direction of travel, to increase or reduce sidewall fusion, or slight alterations to electrical parameters or wire feed in line with the welding procedure specification limits.
This automated feedback loop would eliminate the need for the welding operator to make adjustments, thereby partially de-skilling the existing process and eliminating the relatively lengthy period of supervised training needed to establish an operator as a "suitably qualified and experienced person". In many cases, the repair procedure needed is potentially only an autogenous melt-run over an existing slight defect and again this could be controlled by the algorithmic system.

An alternative aspect of that is to look at using the camera and analysis system for replacement of operator post-welding visual inspection, that is performed on each layer. Usually, during Narrow Groove GTAW, between each weld pass, an operator will simultaneously clean the component and undertake a minimal visual inspection. This inspection could potentially be performed by the vision system when the equipment is not welding (but has an associated training cost with additional samples required). Qualified use of the vision system to perform this inter-pass inspection would reduce the workload of the operator, again reducing the risk of possible fatigue/distraction/accidental missing of an important element.

The system has currently only been applied to a specific use case of Narrow Groove GTAW in the flat position on thick-walled material, but the camera and analysis system can be considered analogous to the eyes and brain of a welding operator. This can, therefore, be applied to other welding processes and joint geometries. Trials internally at TWI have shown initial success on the use of an analogous image analysis system on thin sheet material, and it has also been applied to the Gas Metal Arc Welding (GMAW) process.

There is also the potential for use of the image analysis system on high-speed automated applications, where it is not possible for an operator to observe each of the welding processes, perhaps due to limited space or health and safety concerns. For example, robotic GTAW or GMAW is often performed in an enclosure, which an operator must remain outside. The ability to perform in-process examination at high-speed could lead to improved productivity.

Finally, there is the potential for additional uses in other processes. While these are not yet trialled, theoretically any process which is visually observed by an operator for non-optimal conditions that needs to be corrected could be analysed.

This could be other joining processes, such as laser or electron beam, or completely different, such as cutting processes. For all applications, some form of training will be necessitated, using an experienced process operator to develop the training inputs, but this is akin to the process currently used for training of skilled operators.

4.2 Evaluation matrix

At the end of this project, the overall TRL and MRL of this combination of equipment, application and capability was level 3. The justification for these values is shown in Appendix 1.

Table 4-1: Breakdown of the ending TRL and MRL assessment

Capability level	Guideline descriptors	% of completion			
		25%	50%	75%	100%
TRL 3	1. Analytical and experimental assessments have identified critical functionality and/or characteristics				X
	2. Analytical, simulation or laboratory studies have validated predictions of separate elements of the technology or components that are not yet integrated or representative				X
	3. Performance investigation using analytical experimentation and/or simulations is underway				X
	4. Modelling or simulation systems have been suitably proven to support the programme			X	
	5. Specifications have been identified for the relevant component/subsystem			X	
MRL 3	1. A manufacturing proof-of-concept has been developed and identified as a need within industry				X
	2. Analytical, simulated or laboratory experiments validate paper experiments				N/A
	3. Experimental hardware or processes have been created, but are not yet integrated or representative				X
	4. Materials and/or process have been characterised for manufacturability and availability				X
	5. Initial manufacturing cost projections have been made		X		
	6. Supply-chain requirements have been determined			X	
	7. Specifications have been identified and scoped within project			X	

4.3 Future work

Work will be performed to develop the accuracy of the existing system, and determine the useful limits to which it can be applied, in terms of both welding parameters and joint geometries.

The existing system performs image analysis post-process, with the videos being analysed after welding is complete and recording is stopped. There is an ongoing generation of capability to allow videos to be decomposed into individual frames during the welding process so that they can be forwarded to the neural network with only a delay in the order of milliseconds. This is necessary to allow the system to be able to interrupt the process in the presence of a defect.

Once the accuracy of categorisation is improved with particular regards to the forms of defect that are rectified via lateral movement of the tungsten electrode, investigations into using this data to perform closed-loop control of the welding circuit should be investigated. This may be either as a standalone control system (sending I/O signals to the existing weld controller) or integrated into the existing power source control software. Narrow Groove GTAW systems are sufficiently complex that Windows-based PCs are usually used for control, and so modification is potentially easier than would be for a more traditional PCB controlled system.

More “real world” welding defect data also needs to be acquired, to move the system from the existing lab setup, which has used intentionally created defects to a more industrial environment. At the most simple level, TWI has access to a significant quantity of welding records which may be suitable for this.

Removal of some level of the high technical knowledge required to create, train and test the neural network is being investigated so that the system can move more towards a graphical user interface (GUI), aligned with other aspects of the SIMPLE project which are built into a LabView control system. The end system should allow the collection of visual data correlated to all other analysis signals, segregation by a welding operator and then training of the neural network with additional information to allow ongoing improvement.

5 Recommendation for further research and development

5.1 Route to industrial adoption

Certain elements of the technology are well established. The camera system is on the market, and all of the hardware computational elements are available as stock equipment. The current image analysis software and process are effectively unique, requiring the expertise of a skilled programmer to perform several of the relevant transformations manually. As such, this cannot be considered a process that is easily distributable or usable by a non-expert.

There will, therefore, need to be further work done on producing both full documentation and a graphical software interface that will allow a user to input training videos, perform operator inspection segregation and train the neural network to respond appropriately to input. This would then allow shop-floor operation which would aid the rate of adoption.

While the principles of application of the analysis system are such that it should be possible to apply it to a range of joint geometries and welding processes, there is not currently any information available on the operating window of the analysis system. All trials have been performed on a single joint geometry, using a relatively narrow set of “optimal” welding conditions.

It is necessary to determine the limits of the process, in order to understand at what point the accuracy reduces to an unusable level. This will require multiple series of weld trials, with more significant variations in the process variables and a further series of training and testing data. This also includes changing of the equipment, even if process parameters remain unchanged. Currently, all development has been performed on the Nuclear AMRC Polysoude Narrow Groove GTAW cell, and there are several other manufacturers of similar equipment.

It is also required to train and test the neural network for each distinct application, (outside the determined process/geometry), which means that there is a significant up-front cost relating to the generation of training data, which will also incorporate defect generation and expert segregation.

There are two options to overcome the issue of this training requirement. The first is pre-train a range of different neural networks so that the relevant network can be used for a specific application, where it is determined that the accuracy window of that network covers the application. This would be an extensive exercise, and would not necessarily return sufficient value to a single organisation, that it would be desirable.

Perhaps the most suitable solution to this option would be to license use of a trained system to different manufacturers, while simultaneously collecting all visual data for ongoing expansion and development of additional neural networks. This improves the overall manufacturing industry in terms of defect detection, while not requiring one single company to take significant risk. This could be packaged with a data retention function, eliminating for companies the difficulty associated with retaining large volumes of visual data collected during long-term welding processes.

The alternative approach is to try and "generalise" the system, by introducing more reference images that can be used as a large lookup database for analysis of multiple processes (eg GTAW/GMAW) and multiple joint geometries. It's believed that this would require an increasingly complex neural network architecture, with a much greater number of layers than are currently used (here the analogy to the human brain becomes more appropriate, with the extremely high number of parallel processing units). This would increase processing time and possibly beyond the current levels of computational power to perform in a real-time manner, but this is an ever-moving goal.

However, all of these routes require more recorded visual data than has been collected during this project. TWI has been moving forward with a number of different projects, both internal and with member companies to look at applying the visual analysis process. This includes purely internal research but is also looking at industrial applications including for manufacture of nuclear waste containers and aerospace components. TWI is also looking at where visual data is routinely recorded for later investigation if defects are detected, to see if this data can be used for further trialling and testing of the neural networks developed during this programme.

6 References

[1] Fujita, Y, Ogawa, T, Asai, S, Yamamoto, S, Ohdake, T & Ochiai, M. Development of a welding monitoring system for in-process quality control of thick walled pipe. Welding in the World. 2012, vol. 56, no. 11-12, pp 15-25.

[2] Kim, I-S, Son, J-S, Lee S-H & Yarlagadda, P. Optimal design of neural networks for control in robotic arc welding. Robotics and Computer-Integrated Manufacturing. 2004, vol. 20, no. 1, pp 57-63.

[3] Shin, M L & Yung C. Estimation of keyhole geometry and prediction of welding defects during laser welding based on a vision system and a radial basis function neural network. The International Journal of Advanced Manufacturing Technology. 2015, vol. 81, no. 1-4, pp 263-276.

Remaining Material and Specimens

After completion of the project TWI is in possession of the following material:

Phase 1 and 2 plate offcuts

And the following specimens:

Macro specimens from Phase 1 and Phase 2

Please be advised that TWI will dispose of all remaining material on **31/12/19** and all remaining specimens on **30/9/20**. If you wish to retain any of the material, samples or specimens for longer at your own premises please advise full address details and TWI will arrange for delivery. Please note that TWI reserves the right to make an additional charge for delivery over and above the price charged for this project.

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F. Signal Processing

The University Of Sheffield.

Department of

Physics & Astronomy

Single Manufacturing Platform Environment (SIMPLE) - Stage 2

WP 2.2.5 In-Process Signal Monitoring

SIMPLE-V03

Work Package report

E.S.I.M

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01	17/6/2019	Original issue
02	26/7/2019	Revised issue
03	29/8/2019	Revised issue

Executive summary

- The Enabling Sciences for Intelligent Manufacturing (ESIM) group of the department of Physics and Astronomy of The University of Sheffield (UoS), has successfully developed an in-process signal monitoring system that has been integrated fully into the Single Manufacturing Platform Environment (SIMPLE) demonstrator system. The in-process signal monitoring of DC-pulsed gas tungsten arc welding GTAW welding processes can reveal the presence of faults in the welding process, signified by instability in the welding-arc voltage.
- The in-process sensor system was designed with little knowledge of the end-user operational requirements, in terms of the welding-process parameters or ranges of currents and voltages that were to be measured. There were no preconceptions regarding the potential outcomes of the analysis-algorithm development, beyond the requirement to detect a general process fault, or the presence of GTAW, also known as tungsten inert gas (TIG) welding. As such, the potential capabilities of the detection algorithm to perform fault classification were not anticipated from the outset.
- The SIMPLE project has allowed the ESIM group to begin to understand in greater detail what the limitations of a realistic commercial product will be, and hence to refine the specifications of such a device. Once the end-user requirements have well-established boundaries, the development effort can be focussed on an achievable target.
- Moving forward, considerable effort is required to establish a statistically valid baseline for any given welding schedule in terms of an arc-stability profile. Understanding how to classify welding-process defects based on this profile will require a considerable amount of new data to enable the ongoing development of new classification algorithms, moving beyond the original aims of ESIM’s contribution to the SIMPLE project.

Contents

1 Technical challenge and first principles

1.1 Weld quality validation in the nuclear sector

Welding of high-value components in the nuclear sector requires high-level quality assurance (QA) and quality control (QC) integration within the production process. With the continued adoption of automation into the production line and the application of the Industry 4.0 framework, it is imperative that QA and QC protocols are incorporated into that framework to ensure the ongoing development of the value chain, thus reducing manufacturing lead-times and production costs. Non-destructive evaluation (NDE) testing (NDT) methods such as ultrasonic inspection, magnetic-particle testing and dye penetrant inspection, are typically applied post-weld to measure quality factors. New methods are required that are adaptable to 4th Industrial Revolution (4IR) principles, and which can be automated readily. In-process signal monitoring of production welding processes achieves this goal. Validation of the various in-process signal monitoring techniques is therefore necessary as a route towards nuclear industry compliance.

1.2 A brief overview of available GTAW in-process signal monitoring systems

A variety of gas tungsten-arc welding (GTAW) real-time process monitoring (RTPM) techniques exist including; vision, spectrometry, acoustic and electrical signal monitoring. The focus of this work package is the in-process monitoring of welding-voltage and welding-current signals. Systems already exist in the supply chain that perform this operation to a certain level, and which can be retrofitted to existing welding systems. Some of them are capable of detecting instability in the welding-arc, and they can generate process warnings. However, in general terms, they all have the following limitations:

- Low sample rates (<20 kHz).
- Only record derived signals (i.e. post-processed data).
- Signal processing algorithms not specified.
- Signal processing algorithms not user-definable.
- Decision-making based on simple thresholds.
- Measurement chain not consistent between devices.
- Measurement ranges not consistent between devices.

- Some devices not capable of measurements on GTAW systems.

The points listed above are not considered limitations in the target markets into which the devices are sold, which seem to be dominated by manual gas metal arc welding (GMAW) welding processes (e.g. oil and gas industry). However, a new market for in-process signal monitoring of high-value welding operations is emerging, which may have a more diverse range of measurement and analysis requirements than can be fulfilled by the existing supply chain.

1.3 Requirement for a new GTAW in-process signal monitoring system

The development of a robust, research-capable in-process GTAW electrical monitoring system will meet the emerging demand across multiple manufacturing sectors. This new device has to be highly configurable to facilitate maximum flexibility, as there are many different welding processes spanning the entire manufacturing sector. The system should be capable of providing detailed data for the characterisation of new welding processes and techniques, whilst also being useful as a competitor to existing equipment for the monitoring of well-established welding operations. In order to meet the latter requirement and effectively compete in the market, a set of signal-processing and analysis functions collectively termed *basic analytics* are defined in Figure 1-1 (top). The advanced analytics capabilities (Figure 1-1 bottom) will demonstrate the application of subsystem intelligence, in line with the principles of 4IR. Data obtained via the two types of analytics are retained in an external knowledge-base, to be acted upon collectively by a set of machine-learning algorithms. These algorithms generate *inference engines* – software entities that are redeployed into the commercial product, in a cycle of continuous improvement.

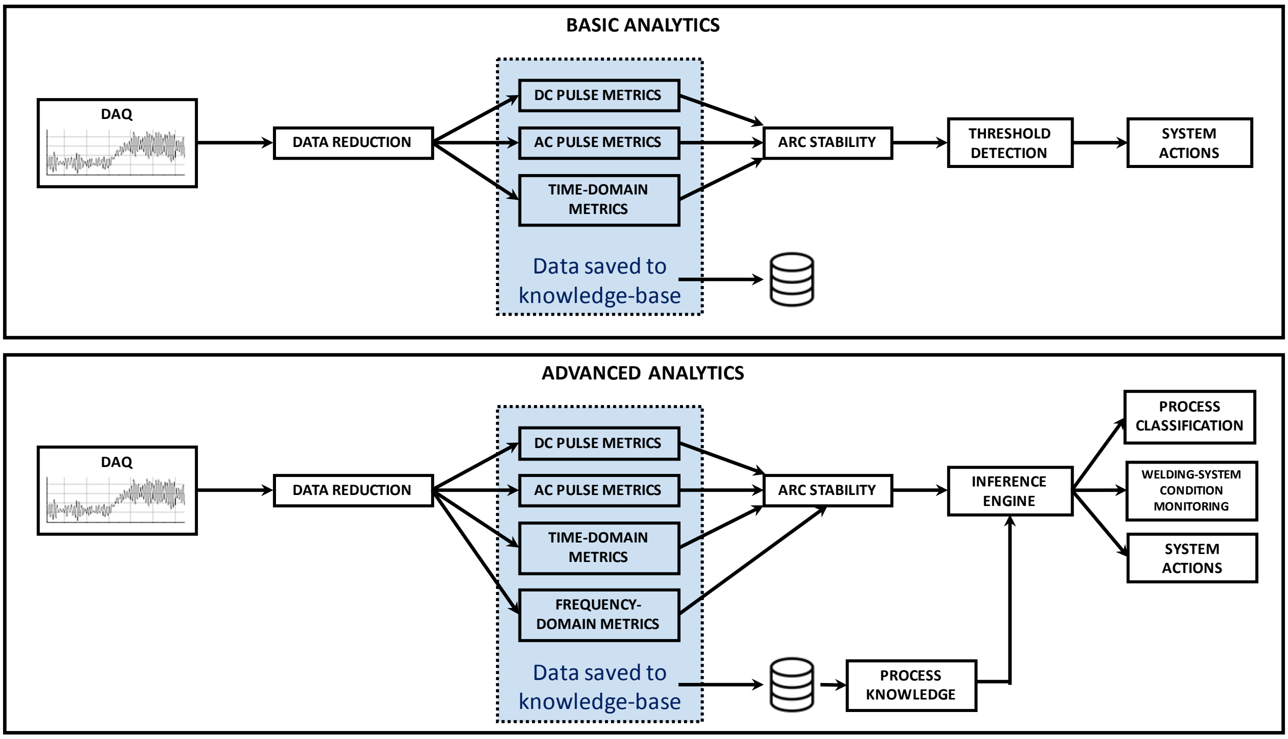

Figure 1-1: Definitions of basic and advanced analytics.

2 Starting MRL/TRL level

2.1 Enabling Sciences for Intelligent Manufacturing research group

The ESIM research group sits within the Department of Physics and Astronomy at the University of Sheffield. In the 2014 REF, the department had over 90% of its research graded as either world leading or internationally excellent, putting it among the top 10 in the UK. ESIM has forged key alliances with institutions and businesses in the domains of high-energy physics (CERN, the European Organization for Nuclear Research), nuclear, automotive, aerospace and VR/augmented reality.

The ESIM team are currently working on ground-breaking research in the areas of applied physics, engineering, and robotics. They have an established record of accomplishment for exceptional research and development in areas such as precision fusion welding, additive manufacturing, collaborative robotics, imaging systems, grasping and manipulation, virtual and augmented realities, and performance evaluation for hazardous environments such as high temperature and radiation.

2.2 ESIM's role in SIMPLE work package 2.2.5: In-process signal monitoring

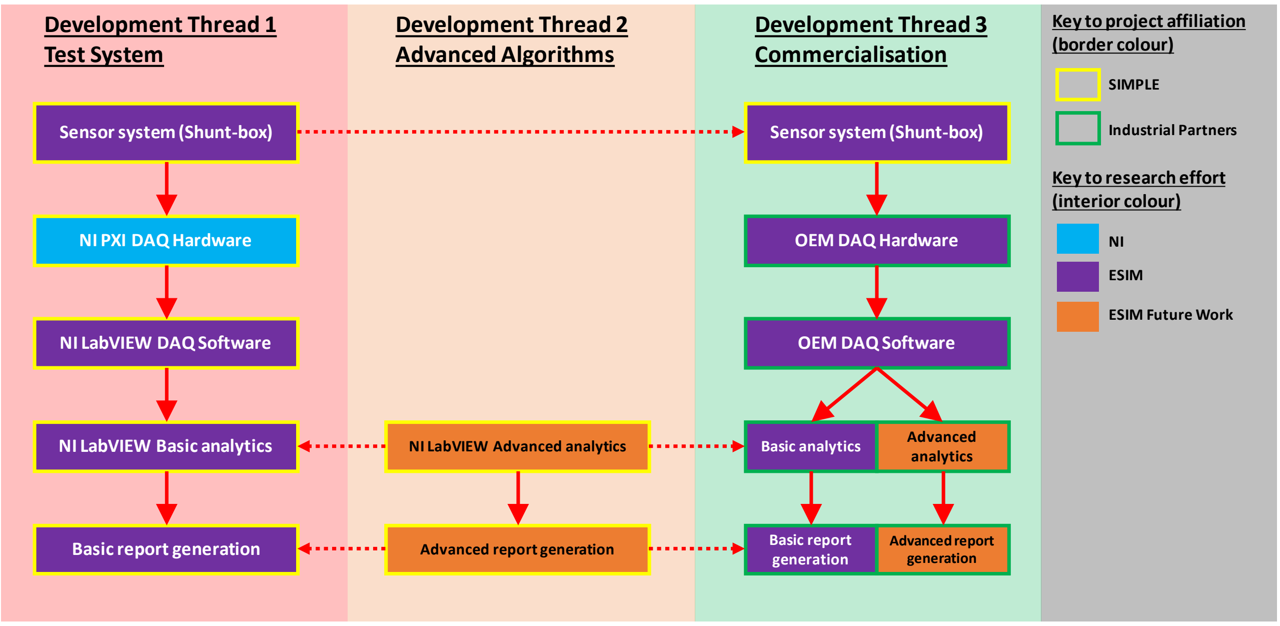

Figure 2-1: Map of WP 2.2.5 R&D threads, showing interconnectivity, research effort, and project affiliation.

There are three main "development threads" that will be referred to throughout this document (Figure 2-1). Development thread 1 (DT1) refers to the development and evaluation of the test system. Development thread 2 (DT2) refers to the development of advanced processing and analysis algorithms that are taking place in parallel with DT1. Development thread 3 (DT3) refers to commercialisation activities and will be discussed later in this document (Section 5.1).

The development of the test system (DT1) has evolved from lower TRL work on a range of welding related research projects within the ESIM group, including narrow-gauge titanium tube welding for the ATLAS project at the LHC, CERN (1), (2). This work has involved the selection, evaluation and integration of OEM current and voltage sensors with high-end DAQ hardware and software to arrive at a starting point of TRL 3 for the SIMPLE project. In terms of the *research and development degree of difficulty scale* (R&D^3) developed by Mankins in 2009 (3), the sensor system development work is considered to be at a level of R&D^3 = 2.

The subsequent stages of TRL advancement will focus in the short-term on DT3, and in the long-term on DT2. The second thread of research and development effort, which is the advancement of real-time signal processing algorithms and data mining for the extraction of welding-process features, is considered to be advanced supplementary work and therefore beyond the original objectives of the work package. However, this line of development is very important, since it will eventually lead to the production of an in-process signal monitoring system with integrated intelligence – a feature that is not currently available in the supply chain. This aspect of the development work is considerably more difficult due to the large amounts of data required for validation, the potentially long development time, and the high level of mathematical complexity. With a difficulty level R&D^3 = 3, this aspect of the work is considered to be at TRL 2.

The commercialisation aspects of the development (DT3) are more complicated, with the outcomes of DT1 and DT2 feeding into that thread. An initial value of TRL 3 is estimated for DT3. A summary of all the initial parameter estimates is presented in Table 2-1.

The justification for these values is shown in Appendix 1.

Table 2-1: Initial research development thread parameters.

Development Thread	Research Difficulty (R&D^3)	TRL	MRL
DT1	2	3	N/A (IP only)
DT2	3	2	N/A (IP only)
DT3	2	3	1

3 Overview of technical challenge for industry

3.1 Evolution from first principles

The development of the core modules comprising the in-process signal monitoring system is discussed, beginning with work that was progressed from low TRL status prior to the SIMPLE project. The advanced analytics concepts (DT2) grew from the test system functionality (DT1), and is now evolving as a separate thread. Details of both development paths are presented.

3.1.1 DT1: Sensor system, DAQ, and basic in-process analytics

The aim of this work package was to develop a robust and flexible system that could monitor the output of a GTAW welding system during the welding process and to apply the developed system to a number of welding operations at the Nuclear Advanced Manufacturing Research Centre (Nuclear AMRC). The challenges in the initial stages of development have centred on the selection of electrical current and voltage sensing technology that was capable of withstanding the harsh electromagnetic conditions generated by a GTAW welding set. The sensors had to be able to tolerate many kilovolts due to arc-strike, yet sensitive enough to measure small changes in voltage (millivolt changes in a 20 V range) and current (up to 1000 A). The sensors that were eventually chosen for the application were packaged into a suitable housing to allow them to be connected in line with the GTAW power supply and the welding torch (Figure 3-1). This portable “shunt box” has been deployed successfully in the ESIM lab at the University of Sheffield, and at the Nuclear AMRC where it has enabled the collection of data from the welding trials with the Polysoude narrow-groove welding system.

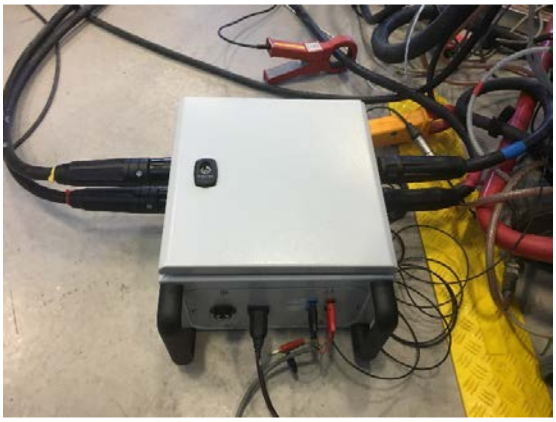

Figure 3-1: Shunt box for GTAW voltage and current measurements.

The shunt box sensors provide two analogue outputs that are read by the data acquisition (DAQ) system. The DAQ selected for this development work is a National Instruments PXI system connected to a high specification PC. The DAQ software has been developed in LabVIEW, which provides all the digital signal processing capability as well as fast real-time streaming of data to hard disk. The input signals from the shunt box sensor system are very electrically noisy, and so digital filtering is required. In all cases, the raw, unfiltered signal is recorded to disk. This allows any retrospective bespoke signal processing to be refined as part of the design process, with the assurance that none of the nuances in the original data is lost in the filtering process.

The filtered voltage and current signals are used in two ways. Firstly, they are recorded to disk. Secondly, they become the inputs to real-time software algorithms. These algorithms are designed to extract useful information from the GTAW signals, the most simple being the presence or absence of an arc (GTAW power supplies perform this measurement internally). An assessment of the welding-arc stability is also provided, which can give an early warning that process variations are occurring.

Having successfully measured and recorded the GTAW welding process data, the core focus of the ongoing software development is the implementation and refinement of algorithms that can provide:

a) Real-time feedback signals regarding the status of the welding process, and
b) Metadata that can be used for post-process analytics.

Initial research by the ESIM team has shown that the arc voltage pulses in pulsed GTAW welding processes contain information relating to the stability of the welding arc. An early version of the arc-stability detection algorithm employed a windowed-averaging of the peak voltage-pulse heights (Figure 3-2). This method successfully reveals that the arc becomes unstable when there is a process fault. By replaying pre-recorded data, the algorithm was able to generate an “arc unstable” signal before the automatic shutdown of the welding system by the GTAW power supply. If the algorithm were to be deployed in a live welding process, this signal could be used to switch off the arc and prevent an unnecessary system-shutdown.

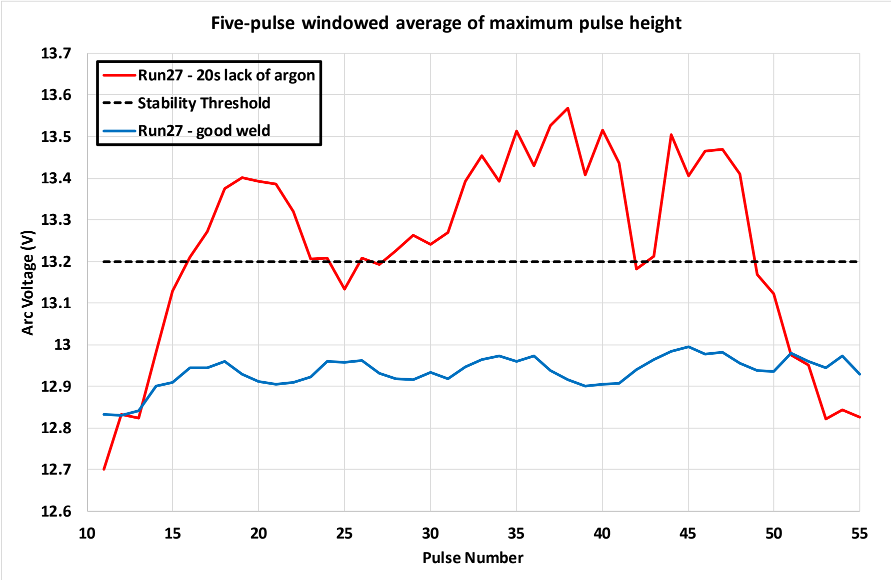

Figure 3-2: Windowed-averaging method of arc-instability detection. In this case, the instability caused by the absence of shield gas (red line) is shown in contrast with a "good" weld profile (blue line). If the arc instability exceeds the threshold then a warning signal is generated.

The arc instability detection by the windowed-averaging algorithm has now been superseded by a new algorithm. This new algorithm takes the time-derivative of each voltage pulse and triggers a sample to be acquired on the rising edge of dV/dt. The derivative voltage data is then fitted to a Gaussian function, which generates three statistical moments of the fitted distribution. These moments are the metadata that can be used for post-process analytics, and by comparing these metadata values between successive voltage pulses, it is possible to determine the onset of arc instability within one pulse (Figure 3-3). This algorithm can, therefore, generate an even more reactive arc-instability signal in real-time. The voltage-pulse metadata is also recorded to disk to facilitate the offline analysis of the welding process. A major advantage that the pulse derivative algorithm has over the windowed averaging method, is that it is not affected by voltage offset. This allows it to be sensitive to voltage pulses that oscillate between any two voltage levels, with no need to know in advance what the threshold voltage for the warning signal should be. However, some prior knowledge of the welding process is still required in order to determine statistically what the stability criterion actually is, but without the requirement for performing a voltage calibration.

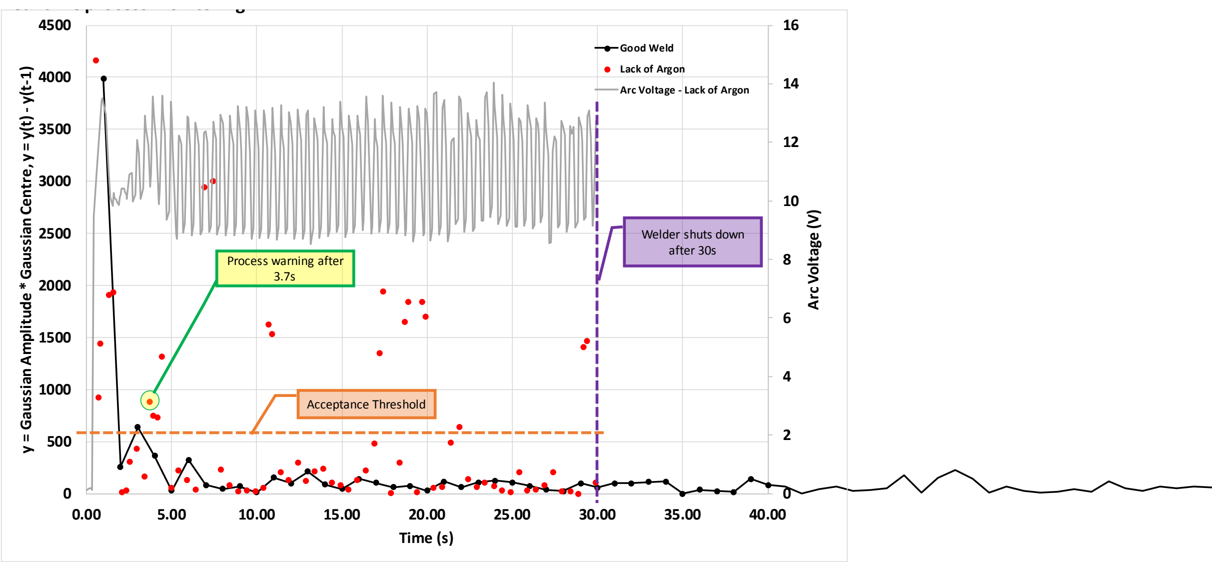

Figure 3-3: The application of the pulse derivative algorithm in real-time process monitoring. After the initial arc strike, the red markers above the acceptance threshold could be used as an "arc-unstable" indicator.

3.1.2 DT2: Advanced analytics

The Gaussian moments of the voltage pulse derivatives are analysed offline. By graphing these moments on a ternary plot, it is notable that the data is clustered around a specific point on the 3-axis grid. The position of the cluster on the grid is dependent on the welding schedule of the process, since different welding voltages, wire feed speeds, travel speeds etc. all affect the performance of the welding arc. The data presented in Figure 3-4 was extracted from five good quality welds of bead on steel plate at the Nuclear AMRC using the Polysoude welding head. It can be seen that most of the pulses are clustered in specific areas of the chart, with a number of outliers. Work is ongoing to understand how the spread of the data clusters relates to the welding process, and more data will be collected to further this knowledge, determine statistical validity, and establish baseline values.

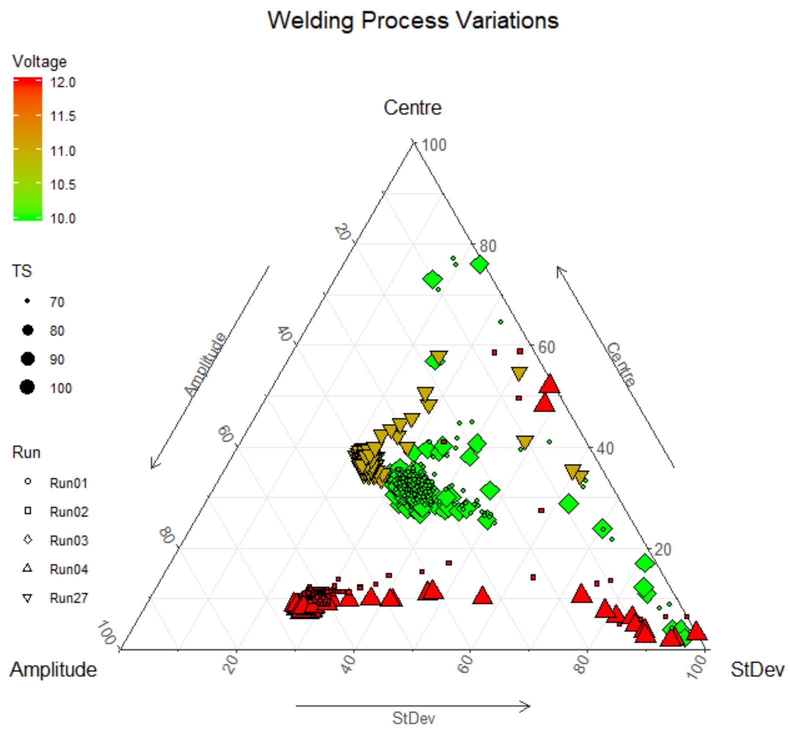

Figure 3-4: Gaussian moments of the GTAW welding voltage derivative pulses. Shows clustering based on arc voltage (colour of markers). The size of the markers denotes the travel speed (TS), ranging from 70 to 100 mms^{-1}. All other parameters are constant: current = 275 A, wire feed speed = 1900 mms^{-1}, and background current = 90.75 A.

This analysis methodology has the potential to enable the classification of defects in the welding process, as indicated in Figure 3-5. The black markers show a standard (good) weld, the blue markers represent a wire misalignment, and the red markers indicate a lack of shielding gas. Further welding trials at the Nuclear AMRC will provide more data for validation purposes.

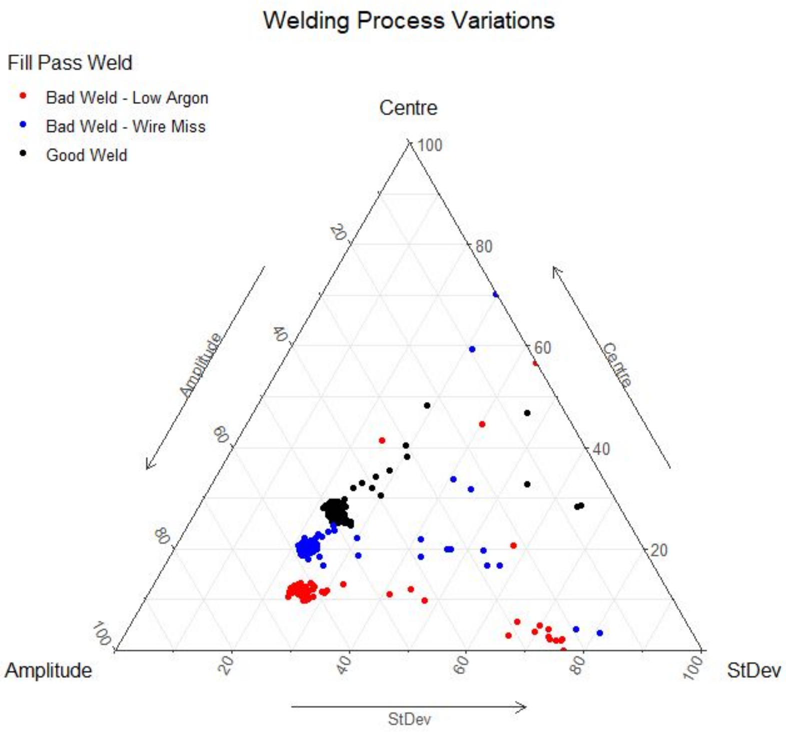

Figure 3-5: The effects of welding process defects on the clustering of the Gaussian moments of the GTAW welding voltage pulse derivatives.

In summary, the algorithms developed to date can determine the stability of the welding arc, and are suitable for deployment as a *basic analytics package* in the test system (DT1) and the commercial system (DT2). The development of an *advanced analytics package* requires considerable further research and development effort. However, this development work can carry on in the background whilst the commercial system (DT3) is progressed to a higher TRL. The eventual outcomes of DT2 will integrate into DT3 as software updates, retrospectively.

3.2 Work conducted and the development path

The element of the work package that required the most effort in terms of time and resources was the initial sensor selection and evaluation phase. The electrical parameters associated with GTAW welding are difficult to measure and harmful to sensitive electronics. The first current sensor that was tested would eventually fail, demonstrating the high risk associated with this phase of the work package. Several other types of sensor were evaluated, but none found to be suitable. The sensors that are presently operational in the monitoring system are now considered robust enough for the application, after repeated trials.

The PXI DAQ system that has been employed to capture the physical signals and the associated LabVIEW software used for analysis and algorithm development is a very expensive, high-end product. This top-down approach to design – in terms of the system capability – was chosen to allow maximum flexibility in the development process. This, in turn, leads to higher returns in the generation of commercially valuable intellectual property, which when vectored through the appropriate commercialisation channels will eventually enable the development of a low-cost, industrially stable end-product. The key risk at this stage is the security of the supply chain for the sensor electronics with regard to commercialization.

The evaluation of the monitoring system has involved a number of welding trials at the Nuclear AMRC. The first set of trials has involved the welding of a bead of filler wire onto a steel plate (Figure 3-6). This experiment has been repeated many times using a variety of welding schedules, and has included the introduction of deliberate faults into the welding process. In all cases the monitoring system has been used to record the electrical outputs of the welding process, in tandem with the measurement of the electrical power inputs to the welding set.

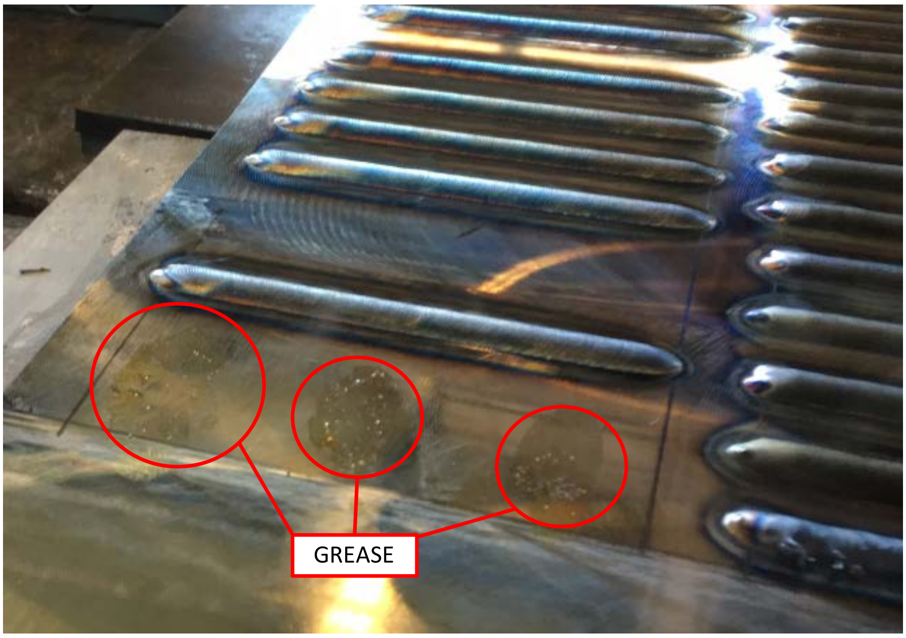

Figure 3-6: Example of bead-on-plate welding trials. Deliberate grease contamination is indicated.

The Nuclear AMRC team has prepared some basic micrographs of the bead welds, which have revealed useful information regarding the bead geometry (Figure 3-7). Recent trials in May 2019 have subjected some of the newly created samples to more detailed metallurgical analysis (see section 3.2.1). Subsequent analysis of this data may, or may not lead to correlations with the electrical data recorded by the monitoring system.

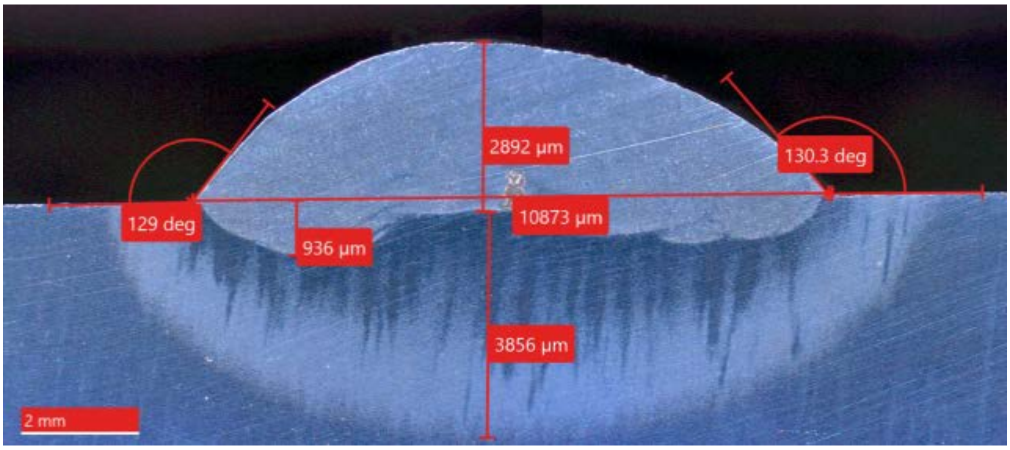

Figure 3-7: Micrograph of bead-on-plate weld showing the bead geometry.

The in-process signal monitoring system has also been used to record and analyse the GTAW signals from the filling of a thick section narrow groove, which simulates a typical nuclear industry metal-joining method (Figure 3-8).

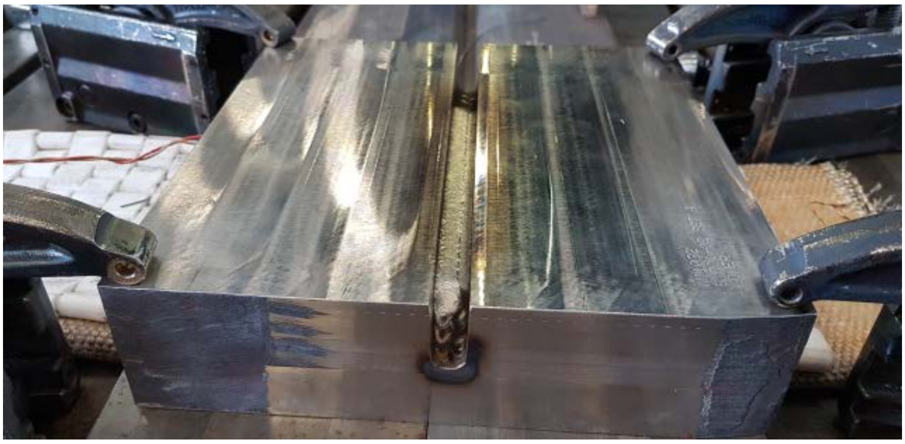

Figure 3-8: Narrow-groove welding trial at Nuclear AMRC

3.2.1 Bead-on-plate metallography

The bead welds were performed on SA508 grade 3 class 2 steel plate. Samples were selected from welds that were performed to the same WPS, but with the presence one of four different process disturbances:

1. No disturbance (good weld).

2. Grease contamination.

3. Low shield gas pressure.

4. High shield gas pressure.

After mounting in resin, the four samples were ground and polished to prepare the surface for etching and microscopic inspection. The sample polishing procedure was as follows:

1. 320 Grit, Contra, 25 N pressure, 2:30 Minutes.

2. 600 Grit, Contra, 25 N pressure, 5:30 Minutes.

3. 1200 Grit, Contra, 25 N Pressure, 5:30 Minutes.

4. 3 µm Colloidal Silica, Contra, 18 N Pressure, 10:00 Minutes.

5. 1 µm Colloidal Silica, Contra, 18 N Pressure, 10:00 Minutes.

This procedure leaves the samples with a scratch free mirror finish, in preparation for chemical etching by immersion of the samples in 2% Nital etchant for 10 seconds, before rinsing in Isopropyl Alcohol. Figure 3-9 to Figure 3-16 show the micrographs depicting the four disturbance conditions. Two micrograph images were taken from each of the four samples – one in the heat affected zone, and one away from the heat affected zone. Clear differences in microstructure can be observed between the heat affected and non-heat affected zones in all cases. However, the micrographs do not suggest any obvious correlation between the type of disturbance and the microstructure of the heat affected zone. This negative result suggests that a different micrographic analysis procedure is required. It does not, however, indicate that there is no correlation between the process disturbances and the weld microstructure. It simply shows that the physical analysis methodology requires a degree of refinement to be useful.

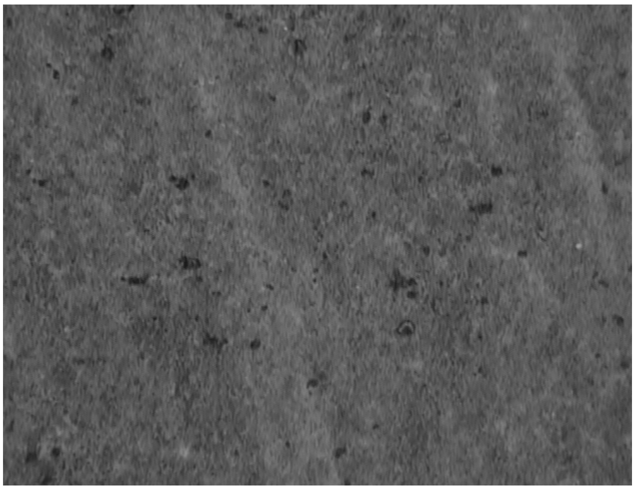

Figure 3-9: Micrograph (x70) of a good weld (no disturbances), away from the heat affected zone.

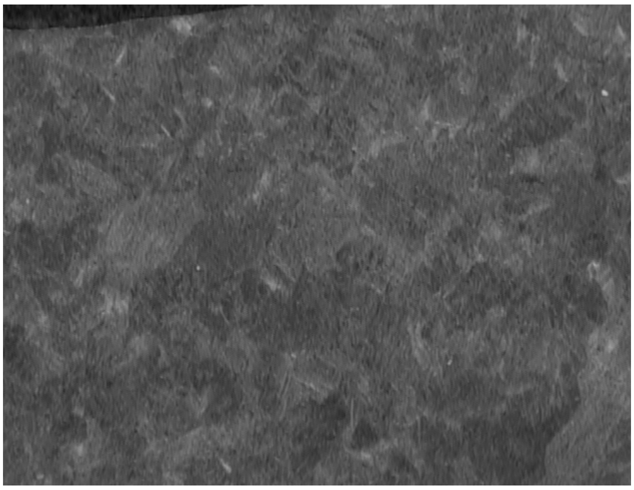

Figure 3-10: Micrograph (x70) of a good weld (no disturbances), in the heat affected zone.

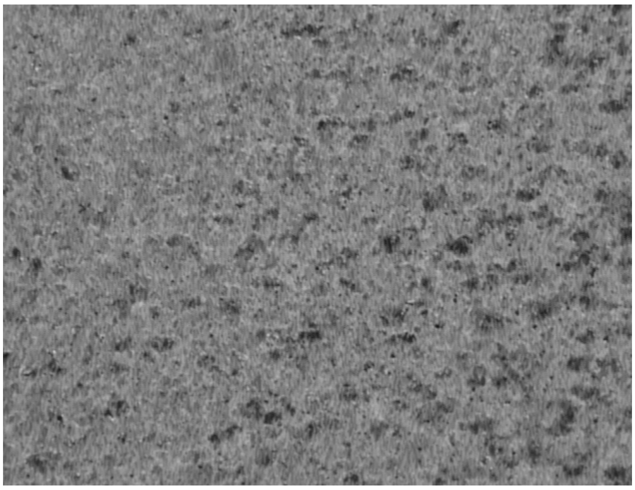

Figure 3-11: Micrograph (x70) of a weld with grease contamination, away from the heat affected zone.

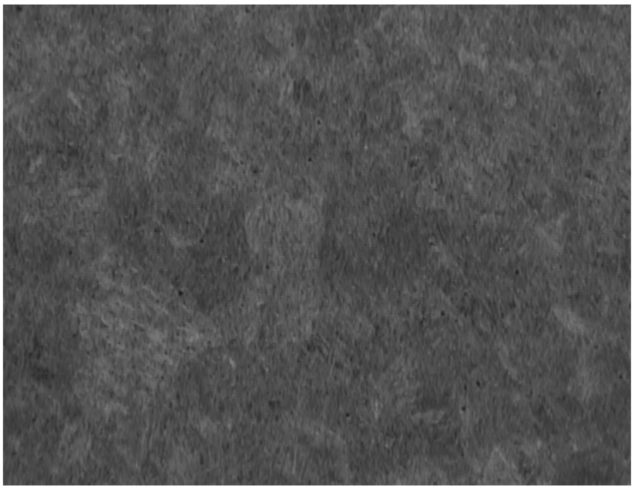

Figure 3-12: Micrograph (x70) of a weld with grease contamination, in the heat affected zone.

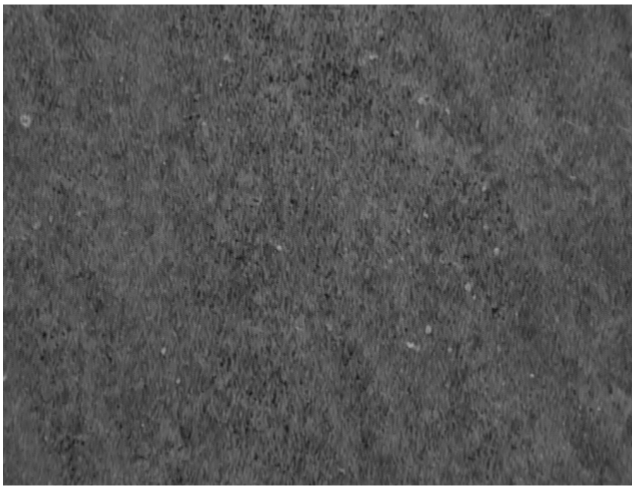

Figure 3-13: Micrograph (x70) of a weld undertaken with high shield gas pressure, away from the heat affected zone.

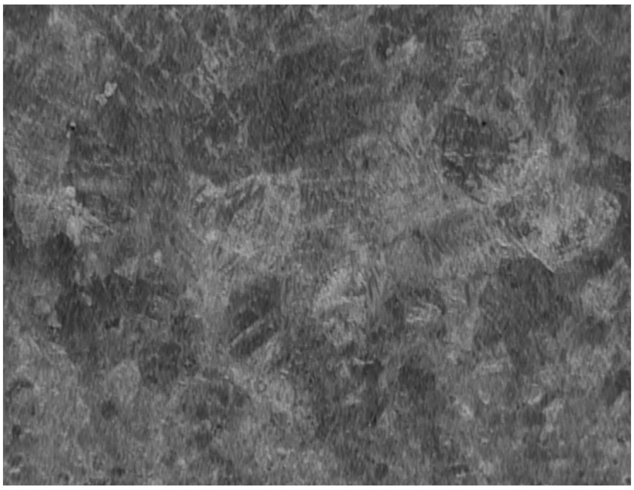

Figure 3-14: Micrograph (x70) of a weld undertaken with high shield gas pressure, in the heat affected zone.

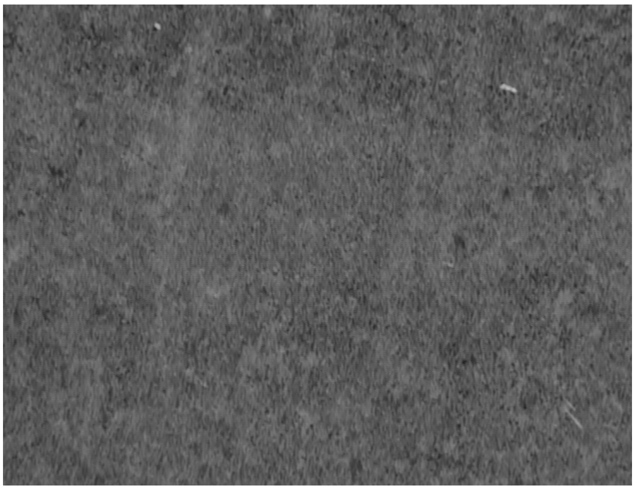

Figure 3-15: Micrograph (x70) of a weld undertaken with low shield gas pressure, away from the heat affected zone.

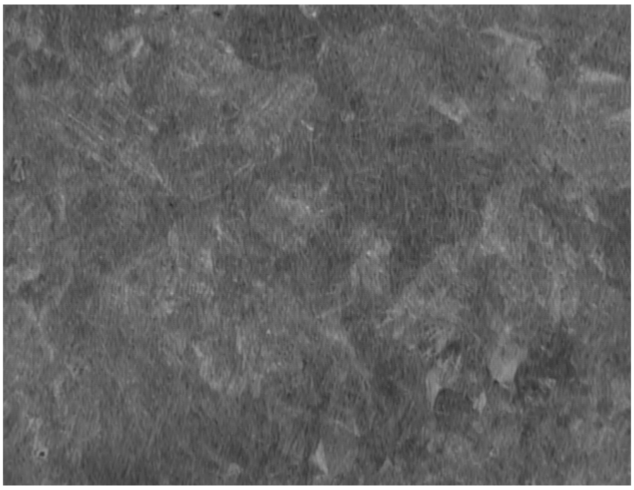

Figure 3-16: Micrograph (x70) of a weld undertaken with low shield gas pressure, in the heat affected zone.

4 End MRL/TRL level

4.1 Potential industrial impact

A highly configurable research-capable in-process signal monitoring system developed by ESIM could have a substantial impact on nuclear sector weld monitoring. A review of the publicly available welding supply chain has revealed that existing products do not have the capabilities offered by ESIM's system. There are two basic methods by which the GTAW arc can be monitored. The first method involves the extraction of the arc control signal as it is generated inside the welding set, before it is fed into the output power amplification stage of the machine. Monitoring equipment based on this principle tends to be manufacturer-specific and not generally applicable to other makes and models of GTAW welding power supply. The data obtained by this method also has the disadvantage of not being truly representative of the actual welding arc, thus rendering the method useless for effective in-process weld monitoring. Table 4-1 summarises the available systems.

Table 4-1: Welding systems with internal process monitoring capability.

Name	Electrical DAQ capability	Compatible with other brands
R-Tech GTAW Welder Digital AC/DC 400 Amp 415v	Unknown	N/A
Parweld XTT503 AC/DC-P1W2RW 500A	Unknown	N/A
Miller Dynasty 800	Unknown	N/A
Polysoude PC-TR	YES. Specifications not available	NO
Lincoln Electric INVERTEC 400TPX	Unknown	N/A
Sureweld Superior AC/DC 422 Inverter	Unknown	N/A

The second method of GTAW arc monitoring is by the use of ancillary equipment to extract data directly from the GTAW welding cables (e.g. ESIM's shunt box). The commercially available ancillary monitoring devices operate over a wide range of input parameters. They have one feature in common, which is that the data sampling rate is in all cases considerably lower than what is offered by ESIM's in-process monitoring solution. The existing systems are inflexible in terms of analysis options, and they do not provide detail of the algorithms used in the generation of test results. They also typically do not allow the user to save the raw, high-density unprocessed data – a feature that is essential for offline post-processing. ESIM's solution operates in a much wider parameter-space and is very configurable. The commercially available ancillary systems are therefore not suitable for cutting-edge research activities, as summarised in Table 4-2. There is a clear need for a high-end, research capable GTAW arc welding in-process monitoring solution as offered by ESIM.

Table 4-2: Ancillary weld-process monitoring equipment.

Name	DC Current	DC Voltage	AC Current	AC Voltage	Sample Frequency	Compatible with other brands
Technoweld EX730 Clamp Meter	YES	YES	YES	YES	N/A	YES
RS PRO ICM A1 Current Clampmeter	<300A	NO	<300A	NO	N/A	YES
Extech ETK35	<400A	<600V	<400A	<600V	At least 10 kHz	YES
Megger DCM340	<600A	<600V	<600A	<600V	At least 400 Hz	YES
TVC Arc Logger XIII	15 – 1999A	0 - 99.9V	15 – 1999A	0 - 99.9V	N/A	YES
Fluke 345 Power Quality Clamp Meter	<2000A	<825V	<1400A	<825V	15.625 kHz	YES
Tenma 72-3500 Clamp Meter	NO	NO	<200A	NO	N/A	YES
Miller Insight Arc Agent	<600A	YES	<600A	YES	10 Hz	YES

By maintaining mutually beneficial links with Nuclear AMRC in particular, ESIM would be able to grow their welding-process knowledge base with data contributed by Nuclear AMRC and its network of nuclear sector partners. This advanced welding-process knowledge would in turn progress the development of the intelligence embedded within the monitoring system, hence refining and continually improving the outputs of the system.

Initial focus on thick-section narrow-groove welding data collection would provide a level of fundamental detail about the welding process under different operating conditions. By limiting the initial investigations to one particular class of welds, the correlations between the in-process data and the finished weld profile (dimensions, metallography, and defects) can be understood fully. Hence the advancement of a new methodology for the determination of weld compliance to nuclear standards will be accelerated.

When the relationship between the development of in-process intelligence and weld-process compliance has been established, it will be possible to tune the methodologies to other classes of welds within the nuclear sector. The next step would be to expand the techniques to other types of electric arc welding, e.g. GMAW, and to develop new partnerships with operators in other manufacturing sectors that depend heavily on compliance monitoring (e.g. oil & gas, aerospace). A similar process of close cooperation with the end-users to gather the vital process data for the development of the process-level intelligence, could, in this case, be led by nuclear sector experts such as Nuclear AMRC. ESIM's in-process signal monitoring solution could potentially lead to a new consultancy-based revenue stream based on the knowledge transfer between ESIM/Nuclear AMRC and nuclear/non-nuclear sector clients. The process of turning raw welding data into advanced process-level intelligence becomes a tradable commodity, in partnership with the physical in-process signal monitoring system.

Looking beyond the commercial benefits in terms of the sales of physical systems and consultancy effort, there is an obvious benefit to the nuclear production processes that involve arc welding. With the advent of "in-process compliance", the need for post-welding inspections will be vastly reduced, and production process validation will become more efficient.

4.1.1 Challenge to MRL assessment

In all but one of the TRL/MRL assessments, ESIM agrees with the peer-review panel. The exception is MRL 3.1. This point is at an MRL completeness level of 25% by the determination of the peer-review panel; however, ESIM has gathered evidence of a clear need for their in-process monitoring solution in the supply chain (market survey in section 4.1). ESIM's assessment is that MRL 3.1 is at a completeness level of 75%. The justification for these values is shown in Appendix 1.

4.2 Future work

Two development threads are expanded upon, DT2 in terms of future algorithm development, and DT3 in terms of ongoing product development.

4.2.1 DT2: Achieving subsystem intelligence

Algorithm development will continue in the key areas of signal processing, data reduction, and data mining. The present system is optimised to extract data from DC pulsed welding systems. There is a clear need to expand the signal processing methods in order to extract data from any type of welding system, DC or AC, pulsed or non-pulsed. When this milestone has been reached, the methods of data reduction in the time domain, and in the frequency domain, will be refined. This generation of reduced data sets will enable established methods in the field of machine learning to be applied, utilising both supervised and unsupervised learning strategies. The resultant inference engine will be embedded into the commercial system (DT3), thus endowing it with subsystem intelligence.

4.2.2 DT3: Ongoing product development: modular systems architecture

ESIM will utilise its network of industrial partners and contacts to progress the development of the hardware, firmware, and software components of the in-process weld monitoring system. The "shunt-box" sensor system should be considered as one "module" in the overall system design. The route to the commercialisation of this module may not necessarily be the same as the route taken by other system modules. For example, the primary DAQ system will consist of several different sub-modules, each with its own development path. Some of the sub-systems may remain at the prototype stage, whilst others will be advanced fully through the TRLs and MRLs.

4.2.3 Acknowledgement of prior art

The in-process monitoring of welding voltage and currents is not a new idea. Procedures that involve taking the time derivative of the welding voltage have been used before (4). Other methods for the interpretation of welding voltages and currents have been documented (5) (6), and ESIM will consider carefully any potential breach of copyright. However, ESIM's approaches to signal-processing algorithm development, and to classification algorithm development, are likely to be substantially different to any prior art in this field of interest.

4.2.4 Publications

Moving forward in the short term, ESIM's conference article for the IIW conference (Bratislava, Slovakia 7-12 July 2019) was submitted. New data collected from a further set of bead-on-plate welding trials in early May will be used in future publications. An abstract for the American Welding Society (AWS) 2019 Annual Conference has been accepted (7), and a journal article for the AWS welding journal has been planned for submission in November 2019. This data analysis will be undertaken in July 2019 (the last month of the project) and so it is not reported here.

5 Recommendation for further research and development

5.1 Route to industrial adoption

Regarding the commercialisation of the in-process signal monitoring system, initial dialogue has commenced with Siemens and National Instruments. Increased exposure to the technology will open new routes to industrial adoption. ESIM has live R&D units deployed in aerospace MRO (Asia) (GTAW, GTAW-Plasma welding), a live R&D unit deployed in the fabrication industry (MIG welding). In parallel to these industrial deployments, the evaluation of IP licensing by the University of Sheffield is ongoing. Table 5-1 shows the formal business relationships with ESIM and UoS.

Table 5-1: Formal business relationships.

Organisation or Company name	Type of relationship (e.g. sub-contractor, supplier etc)	Date relationship started (month and year)
National Instruments UK Ltd	Supplier & Developer of DAQ systems	September 1997
VBC Instrument Engineering Ltd	Supplier & Developer of welding equipment	January 2006

SJ Electronics	Supplier of power monitor	April 2007

Moving forward, ESIM will find more industrial partners, with a view to performing more welding trials (see potential collaborators, Table 5-2). The data obtained in the trials will grow the knowledge base and facilitate algorithm development (DT2), feeding into the refinement of the embedded process-intelligence offered by the system.

Table 5-2: Informal business relationships.

Organisation or Company name	Type of relationship (e.g. advisor, collaborator etc)	Date relationship started (month and year)
ARTC Singapore	Collaborator	2016
Cranfield University	Collaborator	2012
Rolls Royce	Advisor	2011
NIKHEF	Collaborator	2006
CERN	Collaborator	2002
Fraunhofer Institute ISI	Advisor	1999

6 References

1. *Investigation of the TIG orbital welding process on tube-to-tube joints in titanium & stainless steel thin wall tubes.* **French RS, Marin-Reyes H.** Helsinki : IIW International Conference High-Strength Materials—Challenges and Applications, 2015. IIW2015-15/78.

2. *Real-time welding evaluation system assessment using the TIG orbital welding process on ultra-thin wall tube joints in titanium & stainless steel.* **French R.S., Marin-Reyes H., Benakis M.** Shanghai : The 70th IIW Annual Assembly and International Conference, 2017.

3. *Technology Readiness and Risk Assessment: A New Approach.* **J.C., Mankins.** 9-10, pp.1208-1215, 208-1215, Vol. 65. https://doi.org/10.1016/j.actaastro.2009.03.059.

4. **Kilty Alan L., Ludewig Howard W., Wallace Brian L.** *Method for arc welding fault detection. 5,750,957* US, 12 5 1998.

5. *Signature images for arc welding fault detection.* **S.W., Simpson.** 6, s.l. : Science and Technology of Welding and Joining, 2007, Vol. 5. DOI: 10.1179/174329307X213909.

6. *Parametric approach to positional fault detection in short arc welding.* **Xi X., Simpson S.W.** 2, s.l. : Science and Technology of Welding and Joining, 2009, Vol. 14. DOI: 10.1179/136217108X370272.

7. *SIMPLE – Single Manufacturing Platform Environment: Recent advances in real-time pulsed TIG welding-process monitoring and the classification of process variations.* **French RS, Marin-Reyes H, Kitchener BGB.** Chicago : American Welding Society, 2019. Manuscript submitted for publication..

G.Laser Sensor

Single Manufacturing Platform Environment (SIMPLE) - Stage 2

Laser Sensor

NI1032-REP-04

NUCLEAR AMRC
ADVANCED MANUFACTURING RESEARCH CENTRE

Project report

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Revision	**Date of issue**	**Reason for revision or original issue**
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Executive summary

- The objective of this work package was to develop a laser sensor controlling system to monitor weld preparation geometry and to make sure that weld is clear of debris. Moreover, to record the topology of each weld pass as it is laid down. This data can then be used to detect any weld abnormalities on the surface that would subsequently develop into weld defects.
- Due to the challenging geometry of the narrow gap welding process, the use of dual (stereo) sensors was investigated.
- Successful deployment of the system would allow early detection of weld preparation geometry errors, allowing the operator to take corrective action. This will facilitate defect-free manufacturing processes in the future, a key objective of the SIMPLE project.
- A low cost, small, light-weight sensors were selected, which can work in harsh environments (up to 45 °C), and collect data from hot welding processes. The sensors can be easily integrated with the Polysoude welding head or other welding equipment.
- Technical challenges:
    - There is no literature on using stereo laser sensor system of the welding processes
    - Metal surfaces are reflective, and reflections lead to noise in the laser sensor data
    - The geometry of the work-piece is such that no single sensor location can capture all surface data
    - Weld operators cannot detect defects by eye as they occur
    - Laser sensor technology in welding was only applied in laboratory environment and not in a representative manufacturing environment
- Development path:
    - Literature review
    - LabVIEW: ICP algorithm development for stereo data alignment, stitching and 3D model creating
    - Real-time single sensor data processing
    - Algorithm for partial noise removal
    - Single and stereo sensors accuracy testing
    - Virtual method to obtain cross-section of the weld
- Future industrial impact:
    - Detection of the defects in near to real-time and to reduce the processing time
    - Development of bespoke software for welding applications
    - Application in other manufacturing process (additive manufacture in particular)
    - Automation with mechatronics

NUCLEAR AMRC

Contents

1 Technical challenge and first principles

1.1 Problem & Objective

Large scale, thick section nuclear components are typically manufactured by arc based multi-pass welding techniques which require high accuracy and zero defects (1). These techniques tend to be based on Submerged Arc Welding (SAW) and Narrow Groove Gas Tungsten Arc Welding (Narrow Groove GTAW), the latter of which has been the focus of the SIMPLE project.

Welding imperfections can be defined as irregularities occurring in the weld surface, as well as discontinuities and imperfections below the surface. They occur due to the inherent weakness in welding processes and the variable characteristics of metals (2). Weld quality inspections are predominantly carried out after the weld has been completed using post-process inspection methods such as ultrasonic and radiographic inspection (3). When performing multi-pass welds, each weld pass affects the microstructure and sub-surface topology of the preceding pass. Narrow groove multi-pass welding of thick-walled nuclear pressure vessel can take weeks before it is accomplished. If the defects are not detected in real-time, a significant amount of welded material needs to be manually removed to repeat the welding process, or in the worst-case scenario, the high value component needs to be scrapped. This results in lost time and high cost. The detection and correction of defects in real-time will improve the product reliability and quality. Moreover, it will lower the possibility of unexpected failures of the component (4).

This work package investigates the use of laser sensors leading the weld head to confirm weld preparation geometry is correct and that it is clear of debris and trailing the weld head to record the topology of each weld pass as it is laid down. This data can then be used to detect any weld abnormalities on the surface. This transient information can only be collected in process, as the geometric information is lost by the subsequent weld passes. This geometric information relates directly to the quality of each weld pass and hence the quality of the overall weld. As well as improving the weld qualification process, it is envisaged that the study of the relationship between weld pass geometry and weld quality will lead to fundamental insight into the multi pass welding process.

1.2 State of the art

Vision systems based on the principle of laser triangulation brings most of interest from academia and industry (5). The systems based on the principle of laser triangulation was initially developed to measure distance in a one-dimensional (1D) space in the medical field, where laser sensors have been applied to measure the waveform of human arterial pulsation to detect skin surface vibration (6). Lasers sensors are often used for three-dimensional (3D) imaging and reconstruction in automotive (7), architecture, medicine and criminal investigation (8). Moreover, they have been deployed in robotic applications to solve assembly problems (9).

Two dimensional (2D) laser based vision systems have previously been used for weld quality inspection to examine the profile of the generated weld (3) (5) (10) (11) (12) (13). An example of this is the use of a laser vision sensing technology to measure the geometry of a V-weld groove of large-scale aluminium alloy components for aerospace manufacturing (12). The objective of this application was to get a precise measurement of groove geometry pre- and post-weld and to improve the lateral alignment of the welding torch. This was to reduce the work intensity of the operator and consequently improve welding quality by assurance that there are no gaps between the weld and the wall of the groove. The scans were not performed in real-time. Huang and Kovacevic (5) have applied a single laser sensor in real-time to examine laser welding of galvanized high-strength steel, which is widely used in the automotive industry. By processing the data acquired from the vision sensor, small spatters and blowholes were successfully detected. The positions and sizes of the weld defects were identified in 3D profiles. Although laser vision sensing can control the accuracy of the welding process, it has been reported that the scan is only feasible if the surface to be welded is not reflective (14). The reflection from a shiny surface produced high levels of noise which makes data post-processing impossible.

2 Starting MRL/TRL level

Laser sensors are commonly used for inspection in many industrial applications (15) and are at TRL9 if used with the software provided by the manufacturer. As highlighted in the state-of-the-art (section 1.2), in the academic research field, there are few studies regarding the use of single laser sensor to monitor the welding process. However, extending this into stereo laser systems for welding processes with the application of bespoke software, it falls initially to MRL 1/TRL 1, where scientific research has been undertaken but significant development is still required. Similarly, with the application of the single laser sensor for welding applications with bespoke software for real-time data processing, it moves into TRL1/TRL2. The justification for these values is shown in Appendix 1.

3 Overview of technical challenge for industry

3.1 Technical Challenge

The main challenges associated with laser sensors in real-time defect detection during narrow groove gas tungsten arc welding (GTAW) are:

1. **Noise**: High reflectivity components, the workshop environment, and the high intensity of light emitted by the arc, all lead to significant noise and spurious data points in the laser scan profile.
2. **Line-of-sight Issues**: The narrow 2° angle of the weld groove is challenging. Application of a single optical sensor results in the measurement of only part of the weld groove.
3. **Real-time, non-contact measurement of each weld bead geometry before it is buried by subsequent weld passes**: By capturing the geometry of each weld bead that is laid down, a digital 3D model (digital twin (16)) of

the weld can be constructed. Detailed investigation of how this model relates to weld quality will provide an avenue towards a novel weld qualification method (17).

An additional challenge of this work-package is formatting of the laser sensor data in real-time so it can be processed by the AMRC high speed data acquisition and integration system Dewesoft (18). Dewesoft provides the hardware and software that forms the core of the SIMPLE platform. This data acquisition platform is used to store data from various types of sensors in a synchronised format. More information can be found in the system integration report (Chapter I).

The laser sensors use a custom Ethernet data structure, which requires software to be developed to interpret the data into the desired format to be integrated with selected sensing technologies (laser sensors, vision system and acoustic sensor) with the welding hardware and software. Due to limitations of the DeweSoft DAQ software, only a single data point per channel can be transmitted through TCP/IP. To save and display the laser sensor data in real-time, an additional interface software must be written to operate between LabVIEW and Dewesoft. This software must translate the data into an integration-friendly format, and interface with the Dewesoft plug-in structure to successfully acquire the line profile data live.

3.2 Work conducted and the development path

3.2.1 Solution for line-of-sight issue

A laser sensor system was developed to provide real-time profile data of the narrow groove geometry and the external weld surface. The use of a single optical sensor results in non-full profile data (Figure 3-1) due to line-of-sight issues (obstructed vision due to work-piece geometry) and limited field of view of the laser sensor caused by the narrow of the groove.

Consequently, two sensors were deployed at an inclined angle (Figure 3-3) to compensate for the line-of-sight issues. A profile processing algorithm written in LabVIEW is proposed in this study to obtain 2D profiles from the sensors, align the 2D data points, stitch them together, and create a 3D profile of the weld for inspection of weld geometry features and weld surface defects.

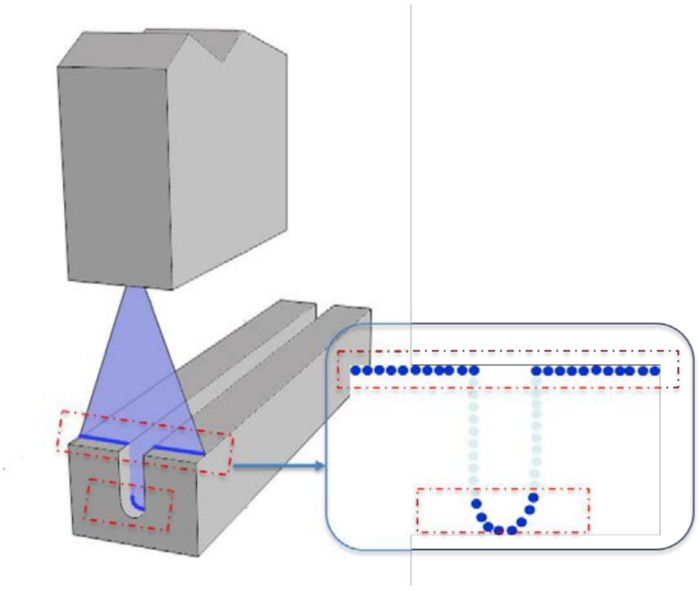


Figure 3-1: The line-of-sight issue: a single sensor can only obtain data from the surface of the work-piece and the bottom of the groove due to the narrow sidewall angle.

3.2.2 Process development

Our hypothesis was that two sensors would be able to obtain full profile data of the narrow groove and allow for high precision in determining the quality of welds and depicting imperfections. Two sensors have to be set at an inclined angle and at a sufficient distance from the groove to compensate for the line-of-sight issues, and increase the field of view, to allow the profile of the sidewalls to be measured. However, due to the low TRL of dual sensor systems applied to real-time welding processes, development of a single sensor data collection strategy was also undertaken to de-risk the development.

The Nuclear AMRC Polysoude welding cell (19) was used for narrow groove GTAW in this project. The Polysoude cell employs a NG8-300-OSC-1C-128 torch (300 mm depth with 8 mm thick torch head) to weld heavy wall thickness materials. Depending on the welding applications, welding can be carried out using a single or multiple pass techniques. Furthermore, the narrow gap torch can be operated in either oscillation mode or simple multi-pass mode. For the SIMPLE project, the torch was operated in multi-pass mode. For the trials the work-piece material was SA508 Grade 3 Class 2 steel of a groove depth range of 30 to 50 mm thicknesses. Initially, bead on plate trials were conducted to obtain the optimised welding parameters for an acceptable weld and were followed by the welding of partially filled butt joints with 25mm deep J-groove machined onto 50 mm thick plates.

Laser sensors were integrated onto the Polysoude head. This is discussed in further detail in Section 3.2.4.1 Experimental Setup and is shown in Figure 3-3. To allow more rapid development of the system, a 3D printed mock-up of the Polysoude welding head (Figure 3-4 (a)) was used to obtain initial data to support software development.

3.2.3 Specification of the sensors

In this work-package, a non-destructive laser-based vision system was applied for the purpose of weld profile inspection. The vision sensor is designed based on the principle of laser triangulation for 2D profile detection (Figure 3-2).

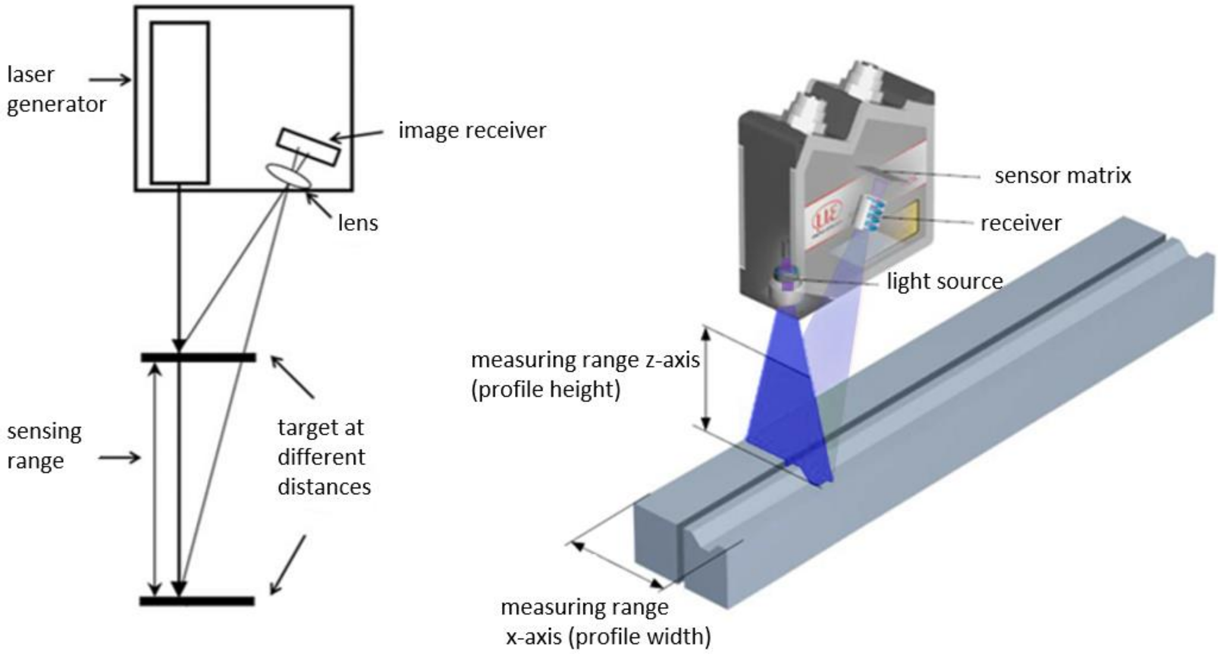


Figure 3-2: Principle of laser triangulation (15) (20).

Using a sensor lens, a laser beam is enlarged to form a static laser line that is projected onto the target surface. The light is reflected on the object and the diffuse reflection is received by the sensor (image receiver), Figure 3-2. Through this, the distance between the light source and sensor element is measured and the distance between the sensor and the work-piece is calculated. This procedure is called triangulation.

Three laser sensors: INvisual CC3100-50, Meta DLS200, Quelltech Q4-120 and Micro-Epsilon 2910-100, were investigated for use in this application. Measuring speed, resolution, sensor weight, working temperature and its cost were key elements considered in the sensor selection (Table 3-1).

Table 3-1: Specification of selected laser sensors.

Parameters	INvisual CC3100-50	Quelltech Q4-120	Micro-Epsilon 2910-100
Resolution [µm]	50	79	12
Measuring speed [Hz]	480	200	300
Sensor weight [g]	350	400	380
Maximum working temperature [^{0}C]	40	40	45
Cost [£]	27,000	32,000	8,145

Due to the challenges with line-of-sight, it was important to have the system that will provide flexibility in synchronising of more than one sensor on one rig. The Micro-Epsilon gapCONTROL blue laser sensors (2910-100/blue light-BL) (15) met project requirements while not having unnecessary hardware/software integrated with the system. The goal of this work-package was to develop bespoke LabVIEW interface for real time data processing. Moreover, those sensors can sustain slightly higher working environment temperature without using additional cooling housing. This system was fit for purpose due to highest resolution, high speed, the potential of building bespoke multi-sensor rig and low cost.

Full specification of the 2910-100BL sensor is highlighted in Table 3-2.

Table 3-2: Specification of the laser sensors.

2910-100/BL	Specification
Resolution [µm]	12
Measuring speed [Hz]	Up to 300
Interface	Ethernet
Output	RS422, Analog, Digital
Points per profile	1280
Max profiles/sec.	4000
Wavelength [nm]	405
Sensor weight [g]	380
Maximum working temperature [^{0}C]	45

Micro-Epsilon gapCONTROL BL laser sensors are specified as reliable to measure hot and glowing metals (such as those found in welding applications). They have shorter wavelength (comparing to 670 nm wavelength of red light laser sensors so the blue light does not penetrate the measurement work-piece (15)). Also the laser sensors are unaffected by the emitted high intensity welding light, because it is blocked with an optical filter from entering the detector and ensures stable signals. The sufficient profile resolution combined with the blue laser line allow for maximum precision for versatile applications. Their advantages include real-time data tracking and the possibility of synchronisation of several sensors if needed. This project required a sensor with a weight of less than 700 g due to weight limitations on the Polysoude head (10 kg total for all sensors and mounts). Moreover, the welding application requires a hardware that can operate in high temperatures. To ensure the laser sensor's temperature remains below 60 ^{0}C, the thermocouples were attached to them, and the reading was taken in real-time during welding.

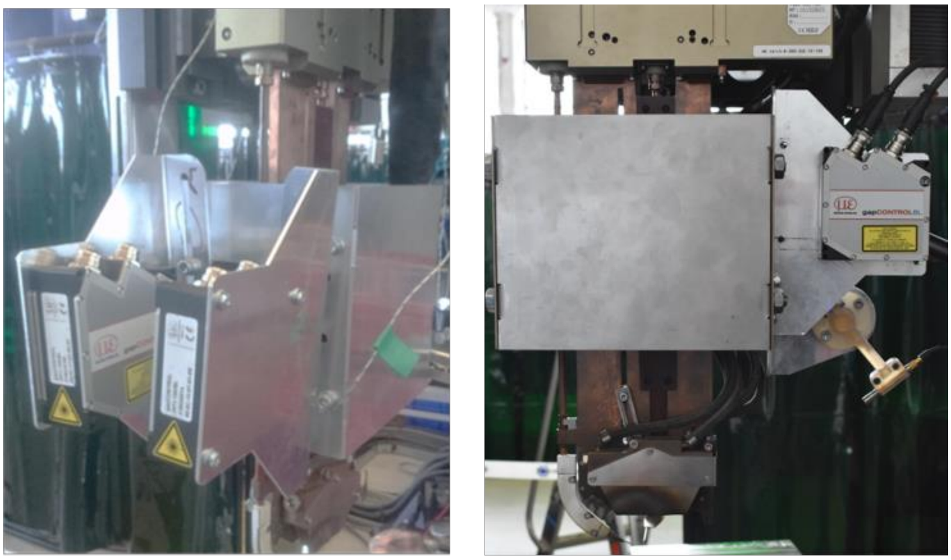
3.2.4 Stereo Laser Sensor System configuration

A stereo sensor system was used to obtain the data from two types of the narrow groove. The particular weld geometry selected for the SIMPLE demonstrator (work-piece with the bottom radius of 5 mm and the sidewall angle of 2°) was chosen to represent the most challenging scenario for collecting laser scan data. This decision was made in order to bring to light any challenges that are specific for difficult geometries. However, custom data acquisition software was needed in order to gather and process data from the laser scanners. In order to develop and test data collection and processing algorithms, good quality data is required. For this reason, a 3D mock weld coupon model with 6 mm bottom radius and 3° sidewall angle was 3D printed. Laser scan data collected from the 3D printed model was used to develop an algorithm for aligning and stitching dual sensor data (section 3.2.4.2), and for development of a real-time profile processing and display program (section 3.2.6.3). These algorithms were tested with the 3° sidewall, 6 mm bottom radius data, but can also be applied to data collected on the more challenging geometry of the actual work-piece.

3.2.4.1 Experimental setup

The bracket that attaches the lasers to the Polysoude head has been designed to allow the angle of the lasers to be easily adjustable for different types of grooves, and mechanically integrated to the front and back of the welding head of the Polysoude system presented in Figure 3-3 (a) and (b) respectively.

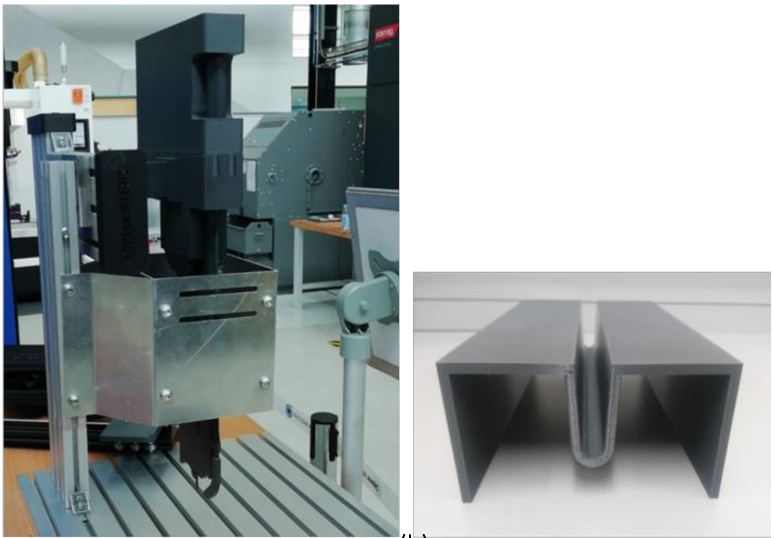
Initially, two sensors were attached at the front of the Polysoude head to ascertain whether there were any debris in the groove prior to the welding process since any contamination ahead of the welding process can lead to defects (Figure 3-3 (a)). However, due to the laser sensor being positioned at ¾ along the work-piece, the scan could only cover the final ¼ of the weld with this configuration. Afterwards, the single laser sensor was fixed at the back of the head to scan the entire work-piece. The sensors were securely attached to the brackets to avoid any vibrations of the setup.



(a) (b)

Figure 3-3: Setup flexibility required for the correction of field of view; where on image (a) stereo sensors are attached at the front of the rig, and on (b) a single sensor is attached at the back of the rig.

To allow more rapid development of the system, a 3D printed 1:1 scale mock-up of the Polysoude welding head was used to configure the best angle and working distance for the two laser sensors (Figure 3-4-a) and capture the initial data to support software development. The sensors were fixed to the brackets and the 3D printed model was travelling (1 mm per second) in y direction to be scanned. Initial data was taken from a corresponding 3D printed model with 50 mm deep weld groove presented on the Figure 3-4-(b).



(a) (b)

Figure 3-4: A 3D printed model of the groove (a) and mock-up of Polysoude welding head (b) with attached plate for the brackets.

3.2.4.2 System Calibration, Data Acquisition and Post-processing

Data acquisition, visualisation and post-processing were done with LabVIEW. The two sensors were inversely synchronised to prevent interference. Inverse synchronisation pulses the lasers alternately, taking one set of data after another.

Each laser sensor operates according to their own local coordinate system. If the integrated system is to produce accurate results then the two coordinate systems have to be synchronised to provide a unified global system (21). For the stereo setup, a laser sensor calibration method has been developed by the modification to the Iterative Closest Point (ICP) algorithm introduced in prior research performed by the Nuclear ARMC (22). Modification of the 3D algorithm was required to process the 2D point data (Figure 3-5). Initially, the point cloud registration based on ICP algorithms were developed by Chen & Medioni (23) and Besl & Mckay (24). ICP is used to find the corresponding matching relationship between two point cloud data sets, namely rotation matrix R' (2×2 matrix) and translation vector T' (1×2 vector), which are the transformation parameters to ensure the accuracy and convergence precision of the algorithm.

If *L* and *R* are two 2D point datasets acquired from two laser sensors S_1 (sensor 1) and S_2 (sensor 2), respectively; then both *L* and *R* are *N*×2 matrices.

N-points sub-dataset $L_c\{m_i|m_i \epsilon B, i = 1,2, \dots N\}$ is taken from *L* If we can find its semantically corresponding N-points sub-dataset $R_c\{m_i'|m_i' \epsilon B, i = 1,2, \dots N\}$ from *R*, then the point clouds registration is to find the 2×2 rotation matrix (*R'*) and a 2×1 translation vector (T') between local coordinates from laser sensor system *L* and *R*. The *R'* and *T'* can be computed by minimising the object function:

$$J_o = \sum_{i=1}^{N} \left\| m_i' - (R' \times m_i + T') \right\|^2 \qquad (1)$$

Scanned data from S_1 has to be fixed and the data scanned from S_2 has to be aligned into the same coordinates using *R'* and *T'*.

Concluding, there is a straightforward relationship between two 2D datasets. ICP search for optimal transformation between points in two datasets. The Iteration stops until some convergence criteria are satisfied e.g. less than a certain value or reaching maximum iteration times.

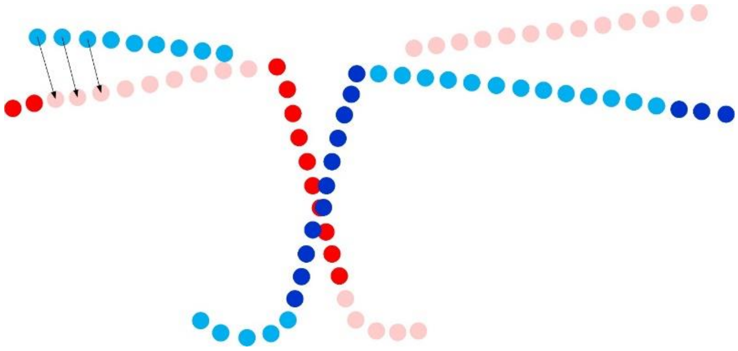
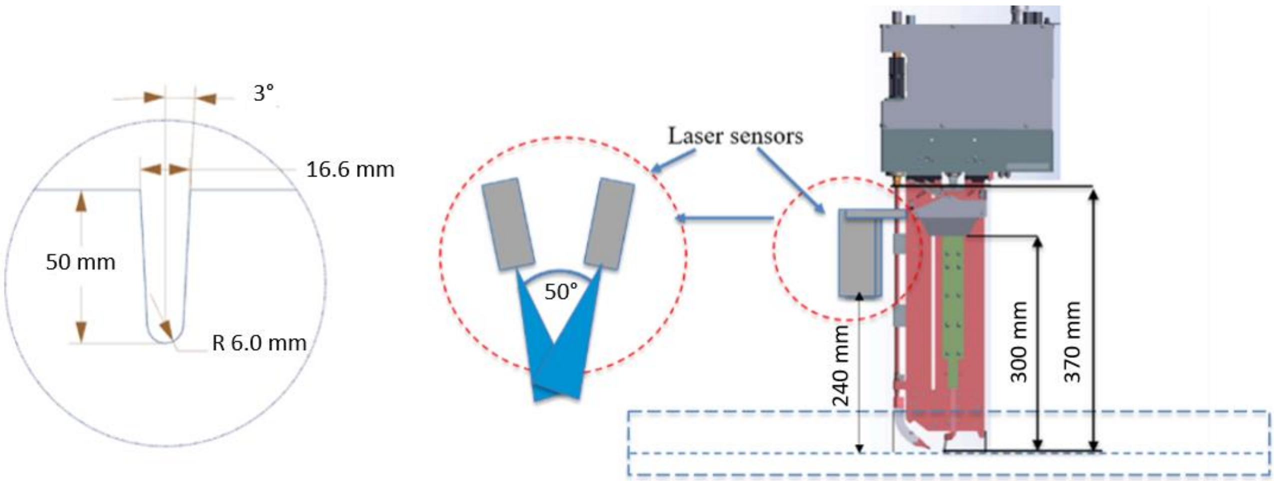


Figure 3-5: Presentation of point's alignment using ICP.

Initial data of the 3D model of the test piece with a 50 mm deep weld groove was obtained and examined. Groove dimensions and 3D model of the Polysoude head are shown in Figure 3-6.



a) b)

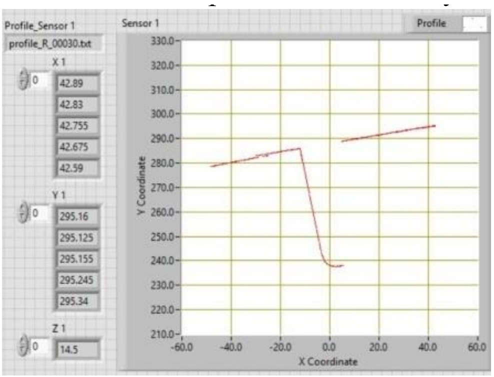
Figure 3-6: 3D printed model groove geometry (a) with the presentation of the setup (b).

After investigating the best configuration of the sensors to image the groove and collecting the data for ICP algorithm development, the stereo setup was applied to collect live data from the welding process. Two sensors were attached to the bracket on the Polysoude as was shown in Figure 3-3. The test pieces being welded had groove depths of 25mm.

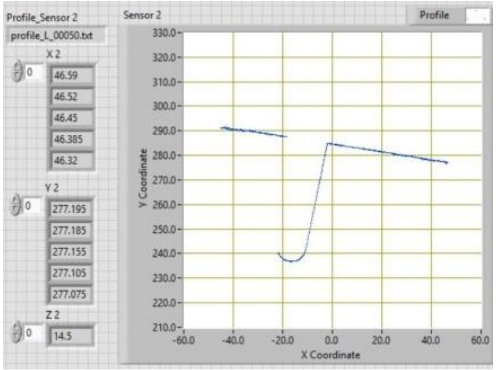
3.2.4.3 Stereo setup results

Good quality data (without significant noise and missing points in the profile data) for post processing was obtained from the 3D printed model at the location and orientation of the sensors presented in Figure 3-6, with 240 mm distance between the bottom of the groove and the sensors, and 50° angle between them.

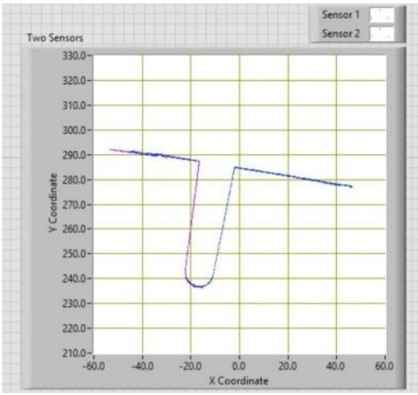
Figure 3-7 (a) and (b) show the 2D points scanned from two laser sensors, respectively. Figure 3-7 (c) shows the 2D data points aligned and stitched together, which can display the full profile of the weld bead. Figure 3-7 (d) depicts the 3D profile of the weld along with its positional information, from which geometrical features are obtained when the dual laser sensor scans across the weld bead surface.



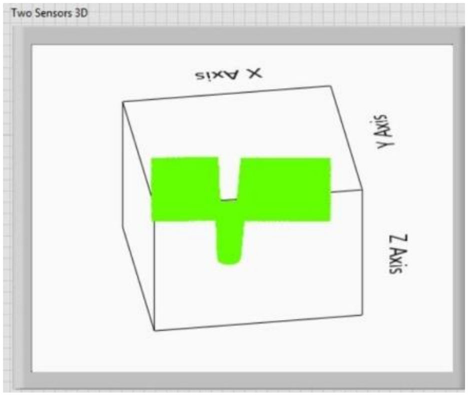
b) Data scanned from S_2



a) Data scanned from S_1



c) Aligned 2D data



d) 3D points cloud

Figure 3-7: Software interface of the dual laser sensors system.

Figure 3-8 presents in more detail plots of subsequent 2D point datasets acquired from the 3D printed model with both sensors. In Figure 3-8 (a), the profiles from each sensor are presented with respect to their own reference frame, prior to the application of the rotation matrix and translation vector, which was explained in section 3.2.4.2. ICP is used to find the optimal rotation matrix and translation vector between points in two data sets to align the reference frames of the profiles. The results of the ICP algorithm with stitched data represents the 3D profile of the groove presented in Figure 3-8 (b). Figure 3-8 (c) shows a magnified 3D plot of the bottom of the groove to highlight the results in more detail. The laser scan data clearly captures the texture (imperfections) of the 3D printed surface, the artefacts from the 3D printing process that are visible at Figure 3-8 (d) in the groove of 3D printed model.

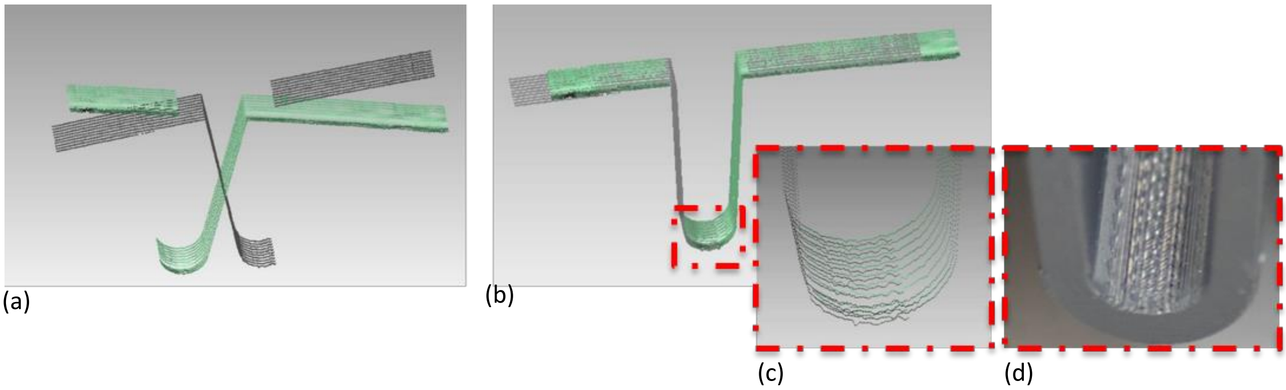


Figure 3-8: Results from the 3D printed model with the highlighted imperfection of the printing resolution.

The data obtained from the live welding trials included some data that was noisy, dislocated or in some cases, the sensor failed to acquire any data points (Figure 3-9). Due to the reflective surface of welded steel, the laser sensors struggled to acquire data from the welding process to be used for post-processing with ICP. Spurious reflections from shiny surfaces are the most major problems in laser inspection. These issues involve light reflecting off of the shiny surface, which results in a lack of data received by the sensor.

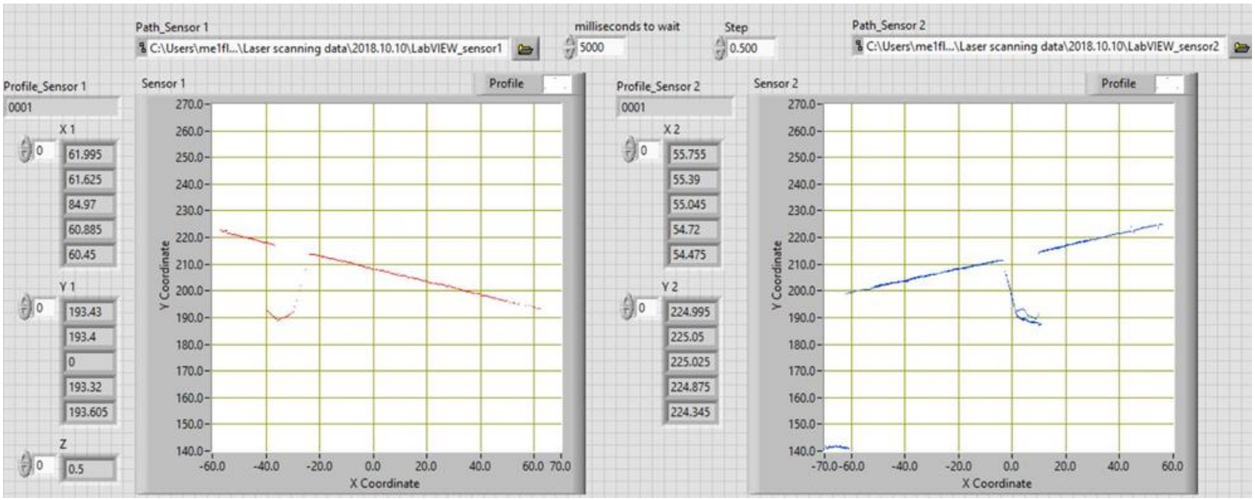


Figure 3-9: Missing and noisy data obtained from the live welding trails.

Moreover, a 2° sidewall angle (as used in the welding trials) was found to be too low to obtain the full profile of the groove by using two sensors. The data from the sidewall was missing and the ICP algorithm was struggling to detect corresponding points from S_1 and S_2 for alignment. When comparing plots from the live welding trails (Figure 3-10 (a)) with results from the 3D printed model (Figure 3-10 (b)), the extent of missing data can clearly be seen.

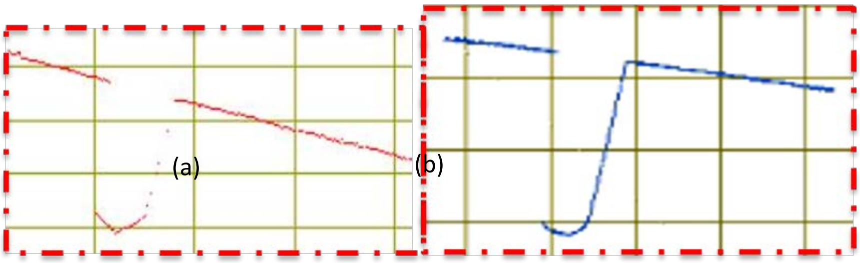
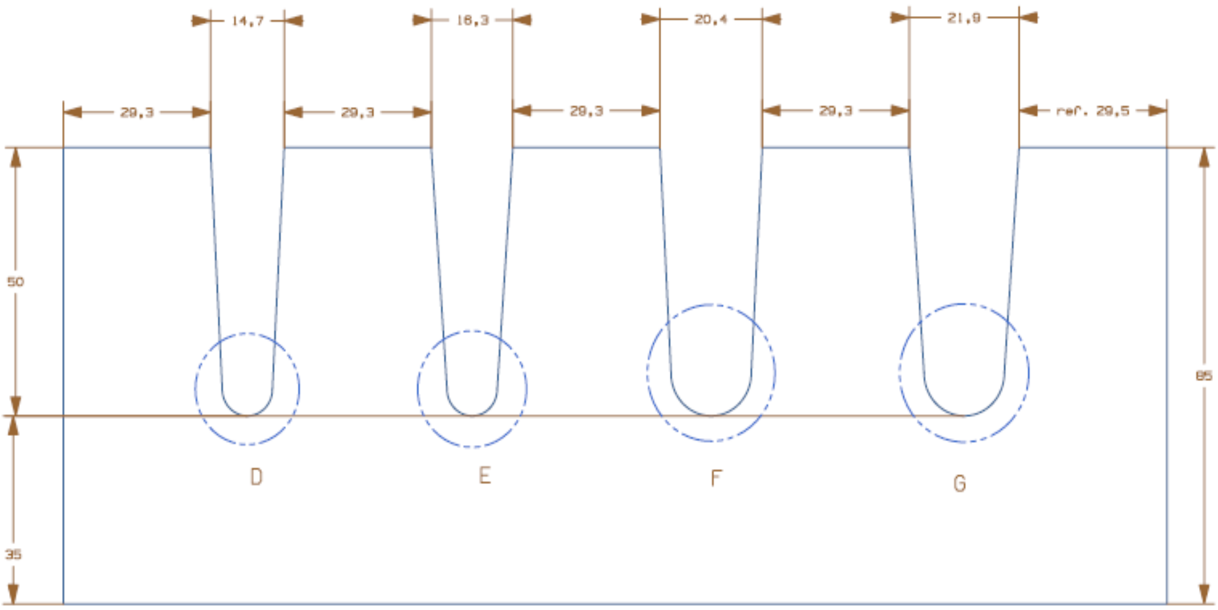


Figure 3-10: Left sensor data; (a) from the live welding trails and (b) from the 3D printed model.

Moreover, it was found that the ICP algorithm is computationally demanding for real-time applications using high speed sensors due to large amount of scanned data. The ICP algorithm requires overlapping of corresponding data from two sensors using an iterative procedure, which requires an unknown time to converge. However, it is a user-friendly post-processing pipeline for delivering reconstructed scan datasets off-line if good quality data has been acquired.

3.2.5 Stereo Sensor Functionality

Initial research has confirmed that stereo sensors can be applied to acquire a full profile of the welded work-piece with the narrow groove if the sidewall angle is 3° or 4° and no reflection occurs. Four grooves have been machined (Figure 3-11) to examine sensors positioned at the inclined angle to the groove.



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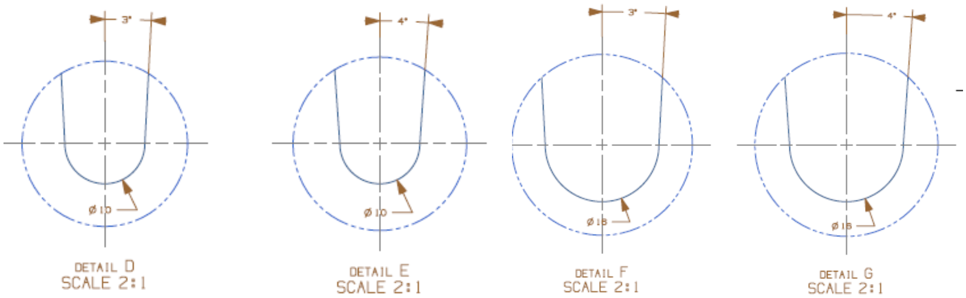


Figure 3-11: Grooves with wider angles for stereo laser sensors rig.

Due to the noise of the scans, anti-reflective spray (CRC Leak & Flaw Detector Spray) used in metrology applications has been applied to the work-piece (Figure 3-12) to prove that with a matte surface we can solve the line of sight issues if the sidewall angle of the narrow groove is larger than 2°.

Figure 3-12: Machined grooves with 3° and 4° sidewall angles.

The left sensor was used to scan the right-hand walls of each groove. The initial results from scans of four grooves are presented in Figure 3-13 Groove (a) has the bottom radius of 5 mm and the sidewall angle of 3°, groove (b) of 5 mm and the sidewall angle of 4°, (c) the bottom radius of 8 mm and the sidewall angle of 3°, and (d) the bottom radius of 8 mm and the sidewall angle of 4°.

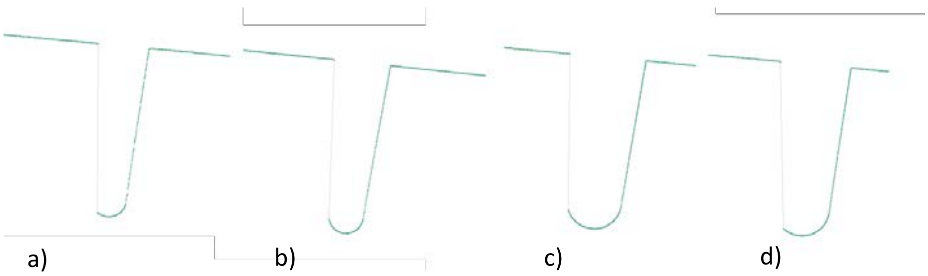


Figure 3-13: Initial data from the left sensors.

Anti-reflective spray cannot be used in the real welding application because it will contaminate the work-piece. However, it was proven (for single sensor research, section 3.2.6.4) that further development of a robust and reliable spike removal algorithm which deals with spurious data that arises from reflections of laser line scanners may result in getting the data of the full profile of the groove. Moreover, LabVIEW program can be designed to collect and process data from two sensors and align them to the same reference frame. If a reflection reduction algorithm is applied, the profile of the groove can be extracted from each sensor individually or the profiles can be combined through averaging of the data points from both scanners.

3.2.5.1 Conclusion

A dual laser sensor scanning system has been developed for the inspection of the weld geometries. Two laser sensors were successfully calibrated with a modified ICP algorithm developed in LabVIEW when using the data acquired from the 3D printed model. It has been proven that the line-of-sight issues for scanning the groove can be solved by using the dual sensors setup while working with the data with no reflections, and 3° angle of the groove. However, results obtained from the live welding trails have shown noisy and distorted results due to the high reflectivity of the work-piece surface. The 2° sidewall angle of the groove was too low for obtaining sufficient overlapping data with the dual sensor system. It was also observed that the reflections are more of a problem when the sensors are positioned at an angle (instead of perpendicular) to the shiny welded work-piece. To mitigate these risks of getting noisy or no data a simplified single sensor system was applied in the remaining welding trials. By focussing on a single sensor, we were able to address the technical challenge of integration with the data acquisition system used to integrate investigated sensors being developed in the SIMPLE project (explained in detail in WP2.3 System integration).

3.2.6 Single Laser Sensor System Configuration

It was shown that the live welding data from the laser sensors was poor and that the spurious signals in the laser sensor profile were occurring due to reflections from the shiny metal surfaces. This happens most noticeably when the laser line hits the surface at a small acute angle (i.e. the sidewalls of the weld groove). In order to remove the spurious reflection data, a data processing and filtering algorithm was required for the current application. A single laser sensor was used to collect the data from the next set of welding trials to facilitate development of this algorithm.

3.2.6.1 Experimental setup

A single laser sensor was mounted perpendicular to the surface of the work-piece. A spirit level was used to ensure that the laser light is parallel to the work-piece. A custom LabVIEW data acquisition processing and display program was developed to carry out the functions that are explained in section 3.2.6.3.

3.2.6.2 Revised Data Processing Strategy

To integrate the laser profile data with the other sensor data within Dewesoft, it is necessary to perform some data reduction in order to transmit only a single data point per channel through TCP/IP. Two strategies were identified:

1. Down-sample the profile data and split the profile up into a separate channel for each x-position.
2. Extract key parameters from the laser profile data before transmission to Dewesoft and send each parameter as a TCP/IP channel.

The second strategy was selected as it requires fewer TCP/IP channels to transmit the data which reduces complications with data integration. It was identified that an additional data processing strategy was required in order to obtain real-time information about the geometry of the groove and generated weld.

3.2.6.3 Geometric Information from the single laser sensor profile

By imparting knowledge of the sample geometry to the data processing algorithm, it is possible to extract information of the features of interest:

1. The left and right extremes of the laser line scan the left and right surface of the work-piece respectively. These sections should be flat (within tolerance which was set as ±0.5 mm for current application), so a simple least squares (LS) fit will give the slope and intercept of each side of the work-piece. The angle between the two surfaces provides an indication of how much the workpiece has warped during welding. The intercept gives the vertical distance of the sensor to the workpiece surface. The data processing algorithm has been developed for this custom application and an additional improvement is needed for more complex welded geometries.
2. The scanner was centred on middle point of the groove. The location of the left and right edges of the groove can be obtained using the same line-fits as '1', by identifying the position where the profile no-longer matches the LS fit to the surface. From the left and right wall locations, it is possible to derive the groove gap width, and the left/right position of the sensor (and therefore the weld head). Since the location of the profile in 3D space relative to the sensor has been derived from '1' and '2', it is possible to re-orient the profile such that the origin is located above the centre of the groove in line with the surface of the plate.
3. In point '3', the profiles are transformed to a consistent X/Z coordinate system. If the Y-coordinate (position along the welding direction) of each profile is known, then subtraction of the current profile from the previous profile at the same Y position would yield information about the current weld bead. Analysis of the subtracted profile between the left and right wall of the groove would give the bead height, width and cross-sectional area and provide geometric and form measurements of the deposited weld at every pass.

The geometric information available from the laser scanner profile data is presented in Figure 3-14. The black profile is the surface of the work-piece (groove and top wall); blue lines represent laser field of view and red area is the section of profile used for line fit and green highlights the centre of groove, which is also the centre of laser sensor. Moreover;

a. The slope of left and right surfaces from the line fit;

b. The warp angle from the difference between the two slopes;

c. The left and right wall location (and therefore gap width) from line fits;

d. The height above surface from intercept of line fit

e. The horizontal offset from the centre of the groove from left and right wall location.

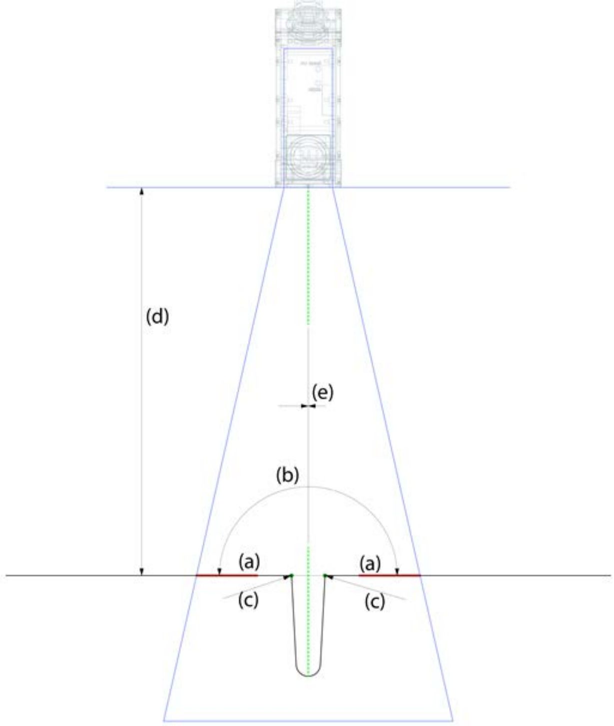


Figure 3-14: Geometric information available from the laser scanner profile data.

3.2.6.4 Resolving issues with reflection

As part of COROMA (25), the Nuclear AMRC project funded by European Union under the Horizon 2020 Programme, work is being conducted on the development of a robust and reliable spike removal algorithm to deal with spurious data that arises from reflections of laser line scanners. Pending finalisation and implementation of this advanced algorithm, a more straightforward strategy was implemented: data points that are outside a threshold determined by the geometry of the work-piece were excluded, and replaced with interpolated data. In this case, the chosen threshold was -28 mm for the lower bound (as the plate was 25 mm deep) and +5 mm for the upper bound (prior experiments determined that capping passes did not lie above this limit). Some spurious data from reflections still remain in the profile, but by excluding the majority of reflective data using the thresholding method, it was possible to extract the geometric information of interest.

In Figure 3-15, the front panel of the data collection is displayed, where (a) are the input controls, and (b) is showing a typical spike in scanned raw data. Yellow and red sections highlight the areas used for line fits which has been explained in section 3.2.6.3 (and Figure 3-14). Part (c) presents a profile of the post processed data, rotated and aligned to a consistent reference frame. No spike filtering was applied in here. In graph (d) of Figure 3-15 the groove width and warp angle against time are presented. Furthermore, (e) is the live display of parameters from data processing ready for TCP/IP communication.

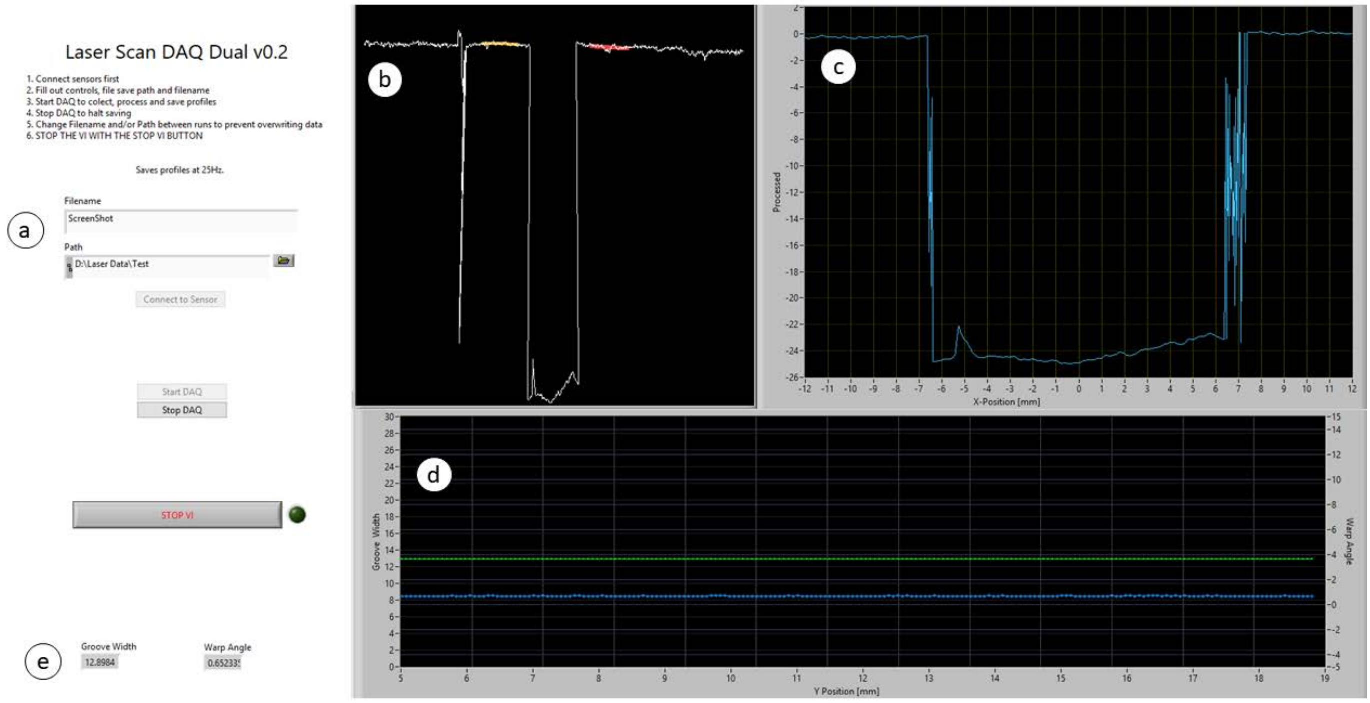


Figure 3-15: Front panel of the data collection.

3.2.6.5 In-line data processing

In order to perform laser line profile data extraction and reduction, a LabVIEW program was developed with the following functions:

1. Interface with the laser sensor via Ethernet.
2. Obtain profiles at 25 Hz.
3. Save raw data in XY format.
4. Fit a line to the left and right sections of the surface (least squares). Derive warp angle and surface height.

5. Find area in the centre of the profile that is below the surface.

6. Determine the left and right wall location. Derive gap width and L/R location.

7. Translate and rotate the profile using derived data to place on a consistent coordinate system.

8. Crop the profile to a defined Region of Interest (ROI) and re-interpolate data to a sensible number of points.

9. Format the derived parameters for transmission via TCP/IP to Dewesoft for integration with the other sensor data.

10. Display the profiles and extracted parameters in a meaningful way.

3.2.6.6 Data Post Processing

The main objective of the laser profile scanner is to provide real-time information of the welded geometry as the weld progresses. Since the raw data from each weld pass is stored, it is also possible to carry out post-processing of the data. This allows fine-tuning of the data extraction parameters and can use more computationally-intensive algorithms which would be too slow for in-line processing. By deriving the distance travelled per frame (assuming constant travel speed) and stacking up the post-processed profiles, it is possible to reconstruct the 3D surface of each weld pass. These surfaces can be exported in common formats such as STL (Standard Triangle Language) for analysis using CAD software. Meshlab, a free open source 3D viewing suite, was used to create the image presented on Figure 3-16 and Figure 3-17.

A number of experiments were carried out with welding parameters known to result in either no defect or a specific defect in the weld. Laser data was collected from each weld pass, and a 3D surface was constructed from these data. Results from Plate 7 Pass 10 are presented in Figure 3-16.

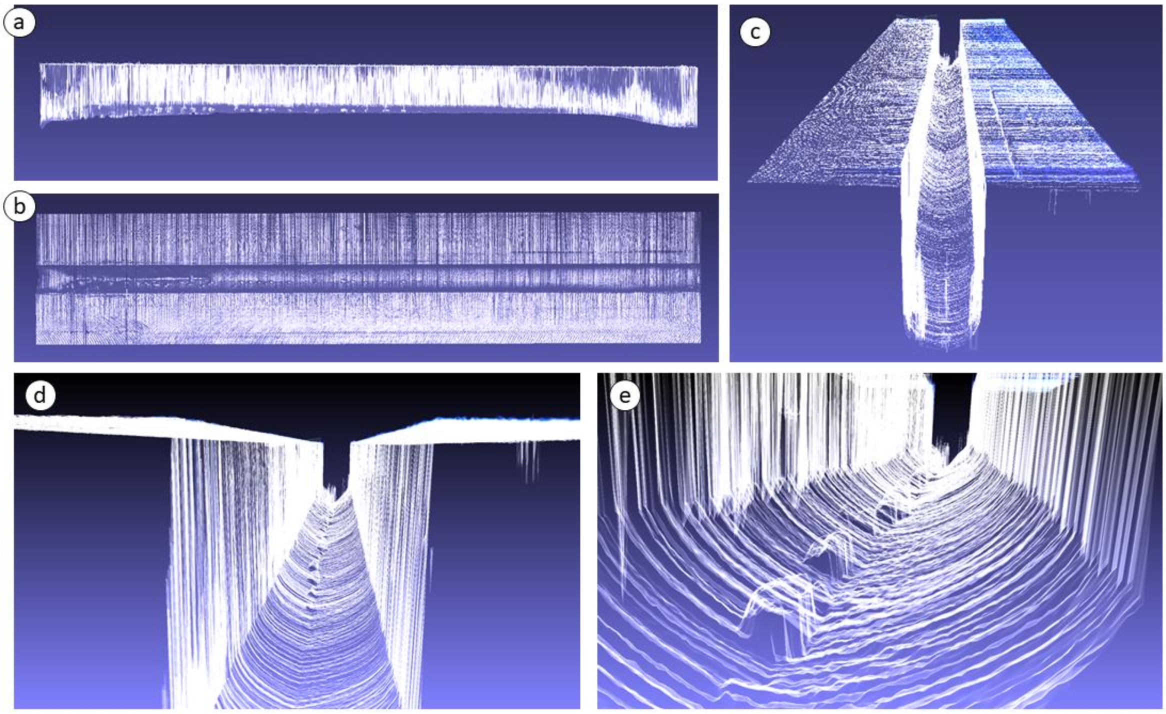
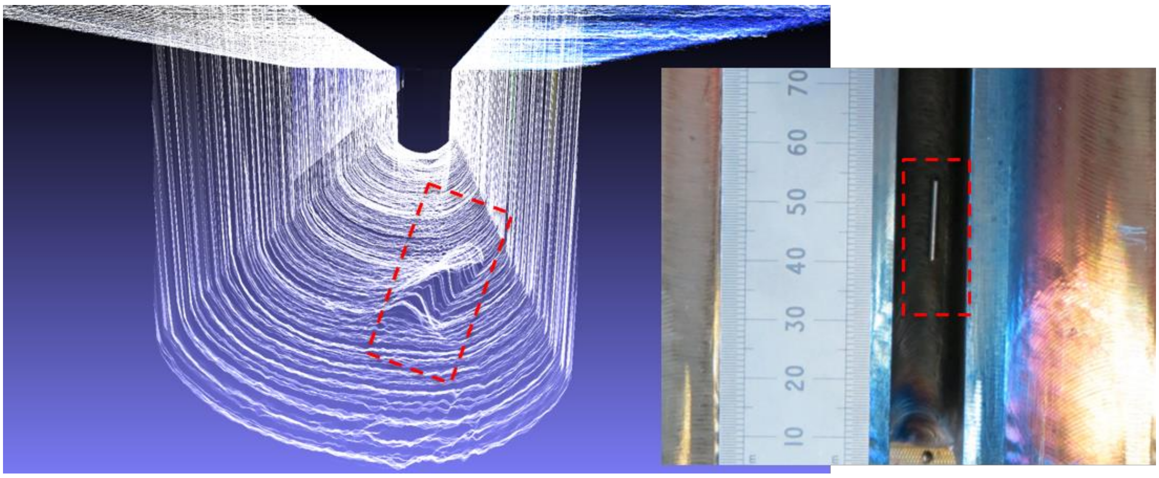


Figure 3-16: Results from Plate 7 Pass 10.

This weld pass presented on the Figure 3-16 was carried out using parameters known to cause sidewall arcing. Figure 3-16 (a) presents a side view of the weld showing features in the groove towards the left side of the weld. In Figure 3-16 (b) top view shows that the features are located in the centre of the groove, and (c) the perspective view down the weld. On the 3D plot (d) the close up shows the location of the weld defect features, and on (e) extreme close up defects. Figure 3-17 (a) depicts a close up of Plate 7 weld pass 21. In this case a 15 mm piece of tungsten presented in Figure 3-17 (b) was deliberately placed in the weld groove to create the debris. The tungsten has slightly shifted during welding.



(a) (b)

Figure 3-17: (a) -results from Plate 7 Pass 21: 15 mm piece of tungsten placed in the weld groove; (b)- tungsten place in the narrow groove.

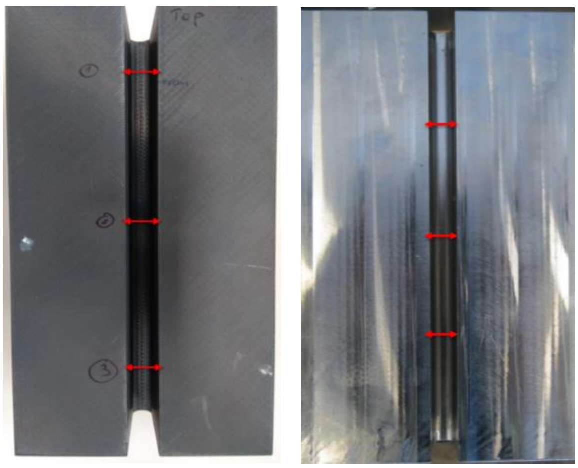
The results presented in Figure 3-17 compared to the results at Figure 3-16 show that the quality of the data is improving after each weld pass when the problem with reflectivity decreases. This phenomenon is due to the natural tarnishing of the surface (25). Following the welding process, the natural chromium oxide film on the metal surface reforms resulting in a tarnished appearance. The quality of the data is significantly improved from the Pass 5 onward due to the reduced reflection of the work-piece resulting from tarnishing.

3.2.6.7 Conclusion

A LabVIEW program has been developed for the single sensor to examine the data in real-time. It gives an opportunity to inspect weld quality during the welding process, and can output key process parameters to Dewesoft for integration. Collecting data from each weld pass gives the ability to go back through the weld history and inspect a 3D model of each bead as it was laid down. This provides a very powerful tool for understanding the formation of potential defects. The limitation of the laser sensors with reflection has been partially mitigated and we can obtain reliable data. Visualisation of the reconstructed surfaces using CAD software allows highly detailed inspection of each weld pass, giving an entirely novel strategy for weld qualification.

3.2.7 System Accuracy

To verify the accuracy of the laser sensor system, three positions of the groove width were selected (highlighted with red arrows on Figure 3-18) and measured using both vernier calliper and laser sensors. For the single sensor the real work-piece was scanned (b). However, for the dual sensors data, the 3D printed model (a) was examined to overcome the problem of reflective work-piece data stitching.



(a) (b)

Figure 3-18: Work-piece with highlighted three widths for accuracy measurement.

The measurement results using the vernier callipers were selected as the benchmark measurement, and then the values were compared with results from the laser sensor system. As the tolerance of the machining dimension of the groove is ±500 µm (21), the vernier calliper are assumed to be sufficiently accurate solution for current application with 25 µm precision (26). Although, the precision of the Vernier calliper is stated to be 25 µm, this does not represent the measurement uncertainty of the measurement system. In order to establish this a full measurement system analysis additional study has to be conducted and this is outside of the scope of this project.

Table 3-3: Data form the accuracy test.

		Vernier Calliper	Deviations (mm)
Single Sensor (real work-piece)	Position 1	14.66	+0.03
	Position 2	14.67	0.00
	Position 3	14.61	+0.06
Stereo Sensors (3D printed model)	Position 1	16.736	-0.31
	Position 2	16.74	-0.23
	Position 3	16.83	-0.17

A standard deviation of the data obtained from stereo laser sensors was 270 µm and for the single sensor 11 µm (calculated from the obtained measurements, Table 3-3). If the measurement uncertainty of vernier callipers is assumed as 25 µm and the observed maximum deviation from standard reference temperature (20 °C) is 2 °C, then the combined standard uncertainty for the stereo sensors is 270 µm and expanded standard uncertainty is 540 µm (95.45% measurement confidence, k=2) and 22 µm for single sensor according to BS EN ISO 14253-2:2011.

3.2.8 Recommendation for laser sensor system future uses

The system development in this work package used commercially available off the shelf scanners. While some data was able to be extracted from the system. Data accuracy could be increased by the development of a bespoke system. The bespoke sensor system could be built to obtain proper spatial resolution for the examined field of view, which would increase the accuracy of the results. In our case, we have been using only 1/4th of the field of view, which micro-epsilon sensors are outputting due to the size of examined weld. To improve the accuracy of the system, it would be recommended (for a new build system) to use sensors that will have a narrower field of view that more closely matches the size of the examined feature. This would allow for higher resolution data to be collected, allowing the system to be able to detect more details from the examined surface. Moreover, in custom setup the intersection angle between planes dissecting laser line and the optical axis of the camera sensor can be examined and modified. Modifying this angle may reduce reflections reflecting back to the sensor.

If recording the data using current LabVIEW software, first raw data has to be analysed (before applying the noise removal algorithm) to see whether any reflection of the laser line has occurred. This is important as if the noise removal algorithm is applied to data with no reflection, the algorithm may exclude some degree of useful information. The algorithm is only suitable for cases where reflection occurs.

4 Conclusions and further work

4.1 End MRL/TRL level

For the single laser sensor, the results of the work covered in this report has achieved the thresholds required for TRL3. Most of the requirements for MRL3 have also been achieved. For the stereo setup, we are at TRL2/MRL2.The justification for these values is shown in Appendix 1.

4.2 Potential industrial impact

While the chosen scanners had difficulty in collecting accurate real-time data in the chosen narrow groove welding application, there is a potential for using the laser sensors for real-time in-process inspection of less challenging geometries and applications. In other research, Nuclear AMRC has already used the same sensors for mapping tool paths, aiding in the alignment of the tool position and for the inspection of defects in robotic grinding for the H2020 project COROMA (25). In this case, a ground surface is coated with a non-reflective paint ahead of the laser scan to remove the issue with reflectivity. The scan data is given in Figure 4-1.

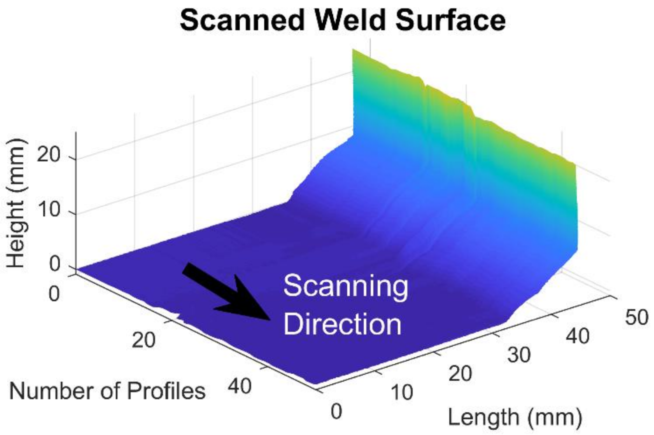


Figure 4-1: Scanned surface of the grinded weld (COROMA (25))

It has been shown that a single laser sensor can be applied in the real-time welding process monitoring (section 3.2.6.6). The major issue is reflection which has to be investigated in more detail. Using laser sensor integrated and validated with other sensing technologies investigated in SIMPLE will build confidence in the welding process and will augment any subsequent non-destructive evaluation (NDE).

Moreover, laser sensors could be applied for process monitoring in wire-arc based Additive Manufacturing (AM). AM of metals requires in-process inspection for integrity verification during the build. There is continuous technological development in AM, however, a lack of viable in-process and post process NDE techniques is a challenge to the industry (26). Real time in-process monitoring would allow corrective actions to be performed before the component is completed to increase component quality.

4.3 Future work

In order to move our laser sensor technology to a higher TRL/MRL levels and closer to commercial adoption, the following future work is required:

1. TCP/IP integration – 1 channel per KPI.
2. Dual sensor mode in real-time.
3. Analysis of post processed data to inform in-line processing development.
4. Store each run for comparison during in-line processing. This will allow visualisation of the current bead profile in isolation.

By stacking up the reconstructed surfaces from each weld pass, it will be possible to take a 'virtual cross section' of the weld at any point along its length. These cross sections can be compared to actual micrographs taken from the weld. This could provide insight in to how the geometry of the weld beads changes from when it was laid down and changes due to solidification and subsequent layers deposited, which will be visible when it is cut and polished for metallurgy micrographs.

The quality of the results can be improved by applying bespoke sensor system designed for required spatial resolution. Higher resolution will increase the quality of the results and there is an assumption that it could have a potential to predict residual stresses distribution post weld caused by thermal expansion. Designing a custom sensor will allow a more appropriate angle between the camera sensor and the laser which will reduce reflections captured by the sensor.

The initial experimental approach taken in this development has shown that to examine a 2° angle groove, three sensors are required; one positioned centrally to capture data from the surface of the work-piece and the bottom of the groove, and two smaller angled sensors each aimed at one of the walls of the groove. This would be best carried forward in a project that would seek to combine data from any number of sensors.

4.4 Route to industrial adoption

Beside the latest development that has been achieved for in-line inspection of welding imperfections with the single laser sensor, this technology is still at low TRL/MRL for immediate industrial adoption. The technical challenges associated with laser sensors for real-time defects detection have to be first fully solved. First of all, the limitation related with noisy data due to high reflectivity of the welded work-piece. It has been partially mitigated with the spike removal algorithm but it requires further development to be adopted by industry. Moreover, for the narrow gap groove, line-of-sight issue cannot be solved and no information about the sidewall can be obtained. A LabVIEW program has been developed for the single sensor to inspect weld quality in real-time. However, it has to be validated with other sensing technologies to provide a high degree of assurance that this process has been properly evaluated before its implementation. Providing a good scientific validation of the technology is necessary to provide convincing evidence that developed bespoke laser sensor technology is effective. It will be considered as robust when required industrial accuracy (may be directly related to a specific problem faced by industry) will be achieved. Moreover, technology precision has to be investigated via repeatability tests. Effective technology has to be reliable, safe and of low cost.

Initial research has shown that the line-of-sight issues for narrow grooves can be resolved by applying three sensors, to collect the data from the bottom of the groove and the sidewalls. However, a multiple sensor mode to process the data in real-time has to be additionally developed.

The standalone sensors are commonly used in industrial applications for automatic quality control and production monitoring (15). The advantage of the SIMPLE project is integration of an array of sensors to prove the quality and to validate the obtained data. As such, the real benefit to industry is the development of a series of integrated sensors, including a laser sensor for weld quality monitoring. Clearly, for industrial adoption, issues such as sensor integration, weld access, and cable management need to be considered and therefore working with an equipment manufacturer would be of significant benefit.

4.5 Engagement with industry/academia

The laser sensor work-package had strong links with other work packages within the SIMPLE project, which resulted in knowledge exchange and support across the consortium. This includes discussions that were carried out with AMRC who has been advising on the further sensors technology for welding applications.

The work on the ICP algorithm development for the stereo sensors data alignment has been published (21) and presented at the Landamap Conference, Rotherham, in March 2019. The 13th International Conference and Exhibition on Laser Metrology, Coordinate Measuring Machine and Machine Tool Performance, was organised by Euspen. Many distinguished international scientists working in vision science, engineering and medicine have attended it. This conference focused on novel manufacturing technologies and machine tools, as well as new developments in measurement techniques, performance evaluation for machine tools.

1. ADVANCED WELDING TECHNOLOGY DEVELOPMENT FOR NUCLEAR REACTOR REPAIR Wei Tang, Jian Chen, Brian Gibson, Roger Miller, Scarlett Clark, Mark Vance, Zhili Feng, Keith Leonard. Tang, Wei, et al. 2018, pp. 67-75.

2. Welding Defects and Implications on Welded Assemblies. F.YusofM.F.Jamaluddin. 2014, Comprehensive Materials Processing, Vol. 6, pp. 125-134.

3. Quality control and assurance in fabrication of welded structures subjected to fatigue loading. Stenberg, T and Barsoum, Z. s.l. : Welding in the World, 2017, pp. 1003-1015. 10.1007/s40194-017-0490-5.

4. The detection of burn-through weld defects using noncontact ultrasonics. Abbasi, Zeynab, et al. 1, 2018, Materials, Vol. 11. 10.3390/ma11010128.

5. A Laser-Based Vision System for Weld Quality Inspection. Huang, Wei and Kovacevic, Radovan. 2011, pp. 506-521. 10.3390/s110100506.

6. A Novel Pulse Measurement System by Using Laser Triangulation and a CMOS Image Sensor. Wu, Jih-huah, Chang, Rong-seng and Jiang, Joe-air. 2007, pp. 3366-3385.

7. Applications of the Integrated High-Performance CMOS Image Sensor to Range Finders — from Optical Triangulation to the Automotive Field. Wu, Jih-huah, Pen, Cheng-chung and Jiang, Joe-air. 2008, pp. 1719-1739.

8. State-of-The-Art and Applications of 3D Imaging Sensors in Industry, Cultural Heritage, Medicine, and Criminal Investigation. Sansoni, Giovanna, Trebeschi, Marco and Docchio, Franco. 2009, pp. 568-601. 10.3390/s90100568.

9. Modelling and Calibration Technique of Laser Triangulation Sensors for Integration in Robot Arms and Articulated Arm Coordinate Measuring Machines. Santolaria, Jorge, Albajez, Jose Antonio and Aguilar, J J. September, 2009. 10.3390/s90907374.

10. Chen, Jian, et al. Improving Weld Productivity and Quality by means of Intelligent Real-Time Close-Looped Adaptive Welding Process Control through Integrated Optical Sensors. 2017.

11. SENSORS AND THEIR CLASSIFICATION IN THE FUSION WELDING TECHNOLOGY. Garašić, Ivica, Kožuh, Zoran and Remenar, Maja. 2015, Vol. 3651, pp. 1069-1074. 10.17559/TV-20131127091427.

12. Laser vision sensing based on adaptive welding for aluminum alloy. CHEN Zhixiang, SONG Yonglun, ZHANG Jun, ZHANG Wanchun, JIANG Li, XIA Xuxin. 2, 2007, Front. Mech. Eng. China, Vol. 2, pp. 218-223. 10.1007/s11465-007-0038-2.

13. Applicability of Robotic Welding for Aluminum Boat Manufacturing Applicability of Robotic Welding for Aluminum Boat Manufacturing. Kah, Paul, et al. December 2014, 2015.

14. Yan, Zhiguo, et al. A survey of the sensing and control techniques for robotic arc welding. 2007.

15. Micro-epsilon. [Online] https://www.micro-epsilon.co.uk/download/products/cat--scanCONTROL--en.pdf.

16. Feasibility of an immersive digital twin. 2018.

17. Feasibility of an immersive digital twin: The definition of a digital twin and discussions around the benefit of immersion. Hamer, Craig, et al. September, 2018, pp. 16-17.

18. DEWEsoft. [Online] https://dewesoft.com/products/daq-systems/sirius.

19. Polysoude, The Art of Welding-, Technical Manual. NG 8-300-OSC-1C-128 torch NUCLEAR AMRC. 2015.

20. Development of a real-time laser-based machine vision system to monitor and control welding processes. Huang, Wei and Kovacevic, Radovan. 2012. 10.1007/s00170-012-3902-0.

21. A dual laser sensor scanning system for inspection of holistic weld geometry. Li, F., et al. 2019. Laser Metrology and Machine Performance XIII. pp. 2-5.

22. Method to automatically register scattered point clouds based on principal pose estimation Feng Li. Stoddart, David. 2017. 10.1117/1.OE.56.4.044107..

23. Laser welding of thin sheet steel with surface oxidation. A.Kar, J.Xie. 10, 1999, Welding Journal (Miami, Fla), Vol. 78, pp. 343-s. 0043-2296.

24. Flack, David. Callipers and micrometers. 2014.

25. COROMA. [Online] https://www.coroma-project.eu/.

26. Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing. Everton, Sarah K., et al. s.l. : The Authors, 2016, Materials and Design, Vol. 95, pp. 431-445. 10.1016/j.matdes.2016.01.099.

27. A Weld Defects Detection System Based on a Spectrometer. Bebiano, Daniel and Alfaro, Sadek C A. 2009, pp. 2851-2861. 10.3390/s90402851.

28. Research evolution on intelligentized technologies for arc welding process. Chen, S B and Lv, N. 2014, Vol. 16, pp. 109-122. 10.1016/j.jmapro.2013.07.002.

29. Sensors for Quality Control in Welding Sensors for Quality Control in Welding. Cris, Sadek, Alfaro, Absi and Mec, Engenharia. 2012, Vol. 17, pp. 192-200.

30. Dewesoft. Dewesoft. [Online] https://dewesoft.com/about-us.

H.Emerging Sensor Technology – Electron Speckle Pattern Interferometry

Single Manufacturing Platform Environment (SIMPLE) - Stage 2

Emerging Sensor Technology – Electronic Speckle Pattern Interferometry

NI1032-REP-05

NUCLEAR AMRC
ADVANCED MANUFACTURING RESEARCH CENTRE

Project report

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Executive summary

- The objective of this work package is to develop an approach to use emerging sensor technologies to measure the deformation in the welding area for dimension as well as to predict the performance of welding. After the stage 1 of the market analysis report it was recognised that there is a clear need for a measurement instrument which is capable of providing a high resolution, fast, three dimensional weld measurement. Speckle based metrology, especially electronic speckle pattern interferometry (ESPI) is selected to design the system.
- The technical motivation
    - Currently there is a lack of a commercially available instrument which is capable of providing;
        - Fast measurement of surface co-ordinates
        - Three dimensional (3D) and full field
        - Non-contact
        - High resolution measurement of welds
    - The current state of the art instruments are application specific and lack flexibility in order to adapt for this application.
    - A flexible portable system based on ESPI which adaptable to different application condition and settings is designed.
- The advantages of the ESPI based process monitoring approach are:
    - Able to provide measurement criteria mentioned in technical motivation
    - Flexible and adaptable in different measurement conditions
    - Field of view can be adjusted depending on the measurement requirement
- Technical challenges
    - Designing, manufacture and setting up the system from scratch
    - Synchronisation of the camera with the movement of the phase shifting device
    - The development of the software capable of extracting the phase information
    - Data acquired by the existing methods for training defect classifier is time-consuming
    - Vibration isolation in shop floor environment
- Development path
    - Literature review
    - Development of the system design
    - Design and 3D print the necessary parts
    - Development of the image accusation software in LabVIEW and image processing in MATLAB
- Potential industrial impact
    - It has the flexibility to adapt to a wide variety of measuring scenarios when compared to commercially-available off-the-shelf sensors
    - High resolution, non-contact, fast, full field and 3D measurement weld deformation and potential to predict residual surface stress by extrapolating the deformation information

Contents

1 Technical challenge and first principles

The emerging sensor work package was specified to meet a need within the manufacturing sector that is not currently satisfied by any commercially available or near to market sensor. After a market analysis in the stage 1 report it was deemed that the largest need, and therefore market pull, was that of a sensor capable of measuring surface deformation that could then be used to predict residual surface stresses of a manufactured component, in a fast and non-destructive manner. This chapter describes work carried out to develop a sensor system capable of meeting this need in a suitable accurate and robust manner.

1.1 Background

This work package focusses on developing a system to measure welding deformities based on non-conventional potential emerging sensor technologies. By employing current research trends and innovative ideas, a down-selected emerging sensor technology that is capable of producing fast, reliable high resolution measurements will be developed to prove the concept.

Welding is a widely used joining process for sheets/frames of similar or different metal types. There are considerable changes in the materials' structural properties around the welding zone. Early detection and measurement of these changes may help to predict the performance of the welded joint.

A variety of methods exist to measure the dimensional properties at the junction of the welds, e.g. laser line scanners and visual imaging, but their resolution and speed of measurement are quite limiting. For example the resolution of optical imaging is in the range of millimetres (1). While the highest possible resolution obtainable by a laser line scanner is in the tens of microns, as it is a line scanner it is not possible to obtain full three dimensional deformation information. So, there is a distinct need in the industry for a system which is able to provide a fast, three dimensional, non-destructive, high resolution measurement of weld dimension.

The optical techniques based on electronic speckle pattern interferometry (ESPI) are able to provide full field, non-destructive deformation measurement with resolution comparable to the wavelength of light (i.e. in the nanometre scale). Along with high resolution measurement of deformation, these interferometric techniques provide the potential for measurement of strain and welding-related stresses. During welding and cooling a large temperature gradient is generated which creates a build-up of stress and strain in the material. This build-up can possibly elevate the rate of deformation at the joint and degrade the performance. It initiates with deformation in the nanometre range, and later causes large deformities and further damage to the component. Hence, any detection of deformation is beneficial for overall performance evaluation of the joints.

The particular system developed in this work package is based on ESPI from the first principle. The commercially available instruments are not suitable for this particular application due to their limited applicability (Table 1-1). This system will be capable of measuring deformation over a measurement area determined by the field of view of a camera and lens assembly. Fields of view from 5 cm x 5 cm to 1 m x 1 m are readily achievable with currently available commercial cameras and lenses. ESPI is capable of measuring deformation over the whole field of view without compromising on high resolution. The speed of the measurement is dependent on the processor and camera speed, which is much faster than other traditional techniques.

1.2 The principles of electronic speckle pattern interferometry

1.2.1 Interferometry

Interference occurs when two or more light waves interact forming a resultant wave that is different in amplitude from that of the interfering waves. There are certain conditions that need to be maintained to see an observable interference pattern (1).

Frequency: The waves must have the same frequency. Waves with different frequencies will not interfere.

Coherence: In order to able to see interference fringes, it is important for the constituent waves to be coherent i.e. the light waves have a constant relative phase. If the relative phase changes too quickly then the interference pattern will also change too quickly and will therefore average out to there being no interference fringes.

Interference is happening around us all the time, even between different frequency components of visible light, however, due to the lack of coherence we are not able to see any interference fringes. It is only with the coherent and monochromatic nature of laser light that we can observe and understand interference.

Phase is important for interference and interferometric measurement as it holds the information about the object. For example, when a light beam is transmitted through an object (Figure 1-1) the phase of the transmitted beam will be an inverse replica of the object's shape. When the beam of light reflects off the object then the phase of the reflected object will be a replica of the object's surface (Figure 1-1). Consequently if we can measurement the phase then we can measure physical details of the object.

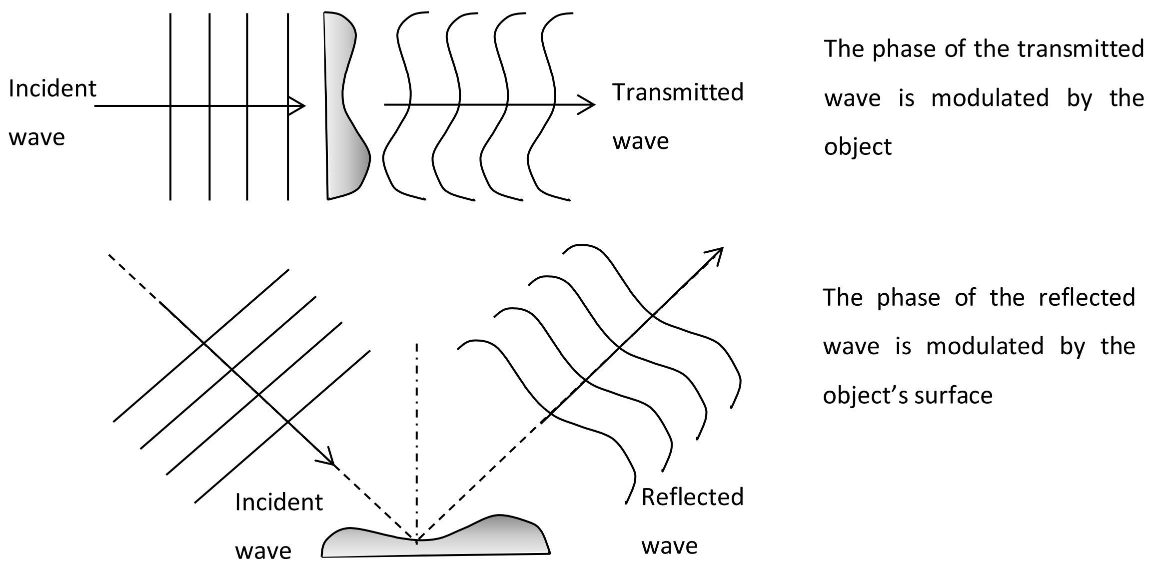


Figure 1-1: Importance of phase

1.2.2 Phase shifting interferometry

Phase shifting interferometry (PSI) is a very popular and effective type of surface measurement technique. The earliest reference of PSI dates back to 1966, while the development of this technique accelerated in the 1970s (2). PSI can be used to obtain fast 3D profiles of surfaces with nanometre-level resolution. PSI typically utilises a laser beam to illuminate the object. A reference beam is also directed towards object that is reflected from a reference mirror attached to a phase shifting device. A camera records the interference between the light that is reflected by the object with a reference light. This interference pattern is a replica or imprint of the surface underneath (as seen in Figure 1-1) and is able to provide an idea of the phase which is related to the surface structure. If I_1 and I_2 are the object and reference beam and $\Delta\emptyset_A$ is the phase difference between them, the interference I , can be expressed as (1)

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\Delta\emptyset_A \qquad \textbf{1-1}$$

In PSI the three dimensional surface topography of the object is measured by sequentially shifting the phase of the reference beam by known amounts and measuring the resulting interference pattern (3). The relative surface heights are then calculated from the fringe data by different processing steps including an unwrapping algorithm to remove the phase ambiguities. The phase shifted images can be represented as below;

$$I_{1A} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\phi_A - 0) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\Delta\phi_A \qquad \text{1-2}$$

$$I_{2A} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\Delta\phi_A - \frac{\pi}{2}\right) = I_1 + I_2 + 2\sqrt{I_1 I_2}\sin\Delta\phi_A \qquad \text{1-3}$$

$$I_{3A} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\phi_A - \pi) = I_1 + I_2 - 2\sqrt{I_1 I_2}\cos\Delta\phi_A \qquad \text{1-4}$$

$$I_{4A} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\Delta\phi_A - \frac{3\pi}{2}\right) = I_1 + I_2 - 2\sqrt{I_1 I_2}\sin\Delta\phi_A \qquad \text{1-5}$$

The phase can be calculated as

$$\Delta\phi_A = \tan^{-1}\left\{\frac{N_A}{D_A}\right\} \qquad \text{1-6}$$

Where $N_A = I_{4A} - I_{2A}$ and $D_A = I_{1A} - I_{3A}$

PSI provides axial resolution in nanometres to the angstrom region with a lateral resolution in micrometres. These instruments are usually limited to the measurement of smooth polished homogeneous surfaces since measurement of rough surfaces with dissimilar optical properties introduces several errors in measurement (3).

A similar principle can be applied to calculate the deformation in an object. However, it is important that the object is not moved from its spatial positon during the deformation.

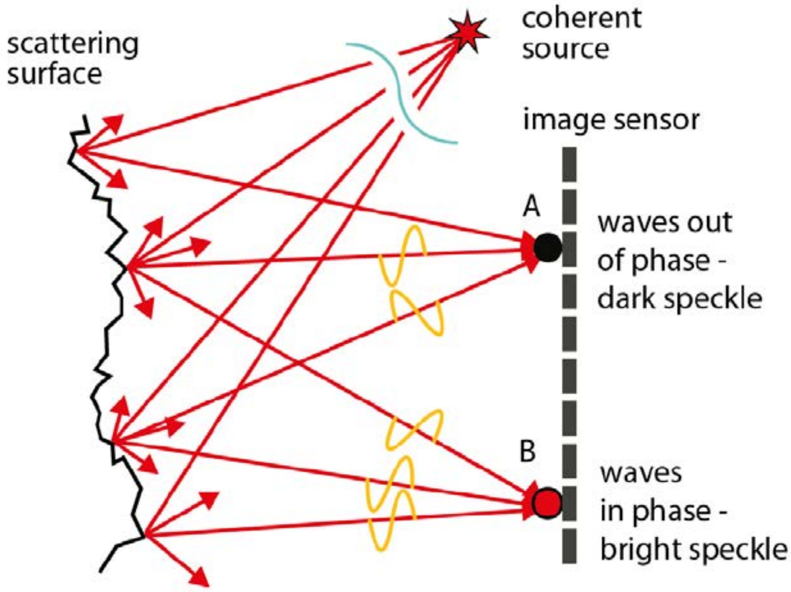
1.2.3 Speckle interferometry

The coherent nature of laser light means that laser interference is observable and the measurement of displacement possible. This is usually demonstrated in the laboratory by using smooth-surfaced objects such as mirrors where interference fringes can be observed. But this also happens with non-smooth surfaces with the resulting interference being observed as speckles. A speckle is a granular appearance of light resulting from interference from different points on the surface, as shown in Figure 1-2 (right). The two contributing factors in the creation of speckles are:

- Spatial coherence of laser light.
- The surface consisting of peaks and troughs that are in the same order of magnitude as the wavelength of the light being reflected.

At any location in space, the resultant field is the superposition of many contributing scattered wavelets. For a diffuse surface (where the peaks and troughs are comparable to optical wavelength), the reflected and scattered wavelets from different features on the surface have a constant relative phase difference, which interferes to create a region speckled with bright and dark spots Figure 1-2 (4) .

The speckle phenomenon has been known since the time of Newton and the theoretical foundation of its understanding was established in the 19th century. However, it only came into prominence with the advent of lasers due to their coherent light source. Initial research regarded speckle pattern as an obstruction and noise which needed to be filtered out to allow useful measurements to be taken. Ultimately it was demonstrated that this 'noise' was in fact an alternative signal that contained useful information (1).



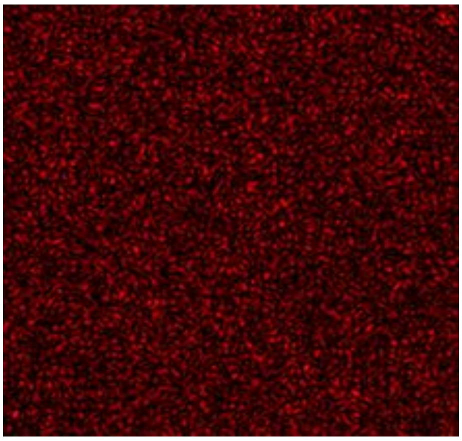


Figure 1-2: Formation of speckle effect (left) (5), example speckle pattern (right)

If the object is deformed, provided it remains stationary then it is possible to obtain the deformation information from this type of interferometry.

Optical surface measurement techniques using phase shifting interferometry have benefited from the development of digital cameras and computers and now offer a realistic alternative for measurement of nanometre-scale deformation. ESPI captures images of objects that have been illuminated with a speckle pattern before and after deformation to quantify the amount of deformation displacement of the surface (6) (7).

Three-dimensional displacements can be extrapolated to provide accurate measurements of residual stress to ensure that the welded joint achieves its design intent. Advanced optical methods due to their noncontact, full field characteristics and high measurement sensitivity have been widely accepted as displacement measurement tools in industry. Of these methods ESPI is the most sensitive and accurate method for full field 3D displacement measurement (8) (9).

ESPI measures displacement by evaluating the phase difference of two recorded speckle interferograms under different loading conditions/deformation. Combined with a phase shifting technique, ESPI systems can measure 3D displacement with nanometre level sensitivity (4). Depending on the type of induced deformation, the object can deform in either the x-y plane (in-plane), or in the z plane (out-of-plane). For a better understanding of the system deformation, it is important that the ESPI system can be designed to measure both in-plane or out-of-plane deformation (shown in Figure 4-1 and Figure 4-2).

1.3 Current commercially available instrumentation

The application field of each commercially-available system varies widely; however, the measurement principle is based around speckle measurement techniques. A review of the commercially available systems is given in Table 1-1. These technologies are either ESPI or a variation called shearography where the design and application of shearography is slightly more complex than ESPI as it includes another interferometer in the design. For all the techniques, the primary measurement parameter is deformation that can be further extrapolated to measure stress and strain.

1.4 Commercial system or build system from first principles

Only one of the sensors listed in Table 1-1 had the required operating parameters for measuring the deformation before and after welding in narrow grooves – the one provided by American Stress Technologies (10) but this was incapable of operation without its associated hole drilling capability. Consequently, none of these systems could be used for this work package without significant mechanical alteration which would have immediately brought into question the validity of any subsequent experimental results.

It was therefore decided that a design and build approach would be more appropriate in achieving to the technical challenge and to ensure we had full control over the experimental process.

Table 1-1: Commercially available ESPI systems

Service provider	Technology	Application	Disadvantages for Narrow Groove GTAW
Dantec Dynamics Ltd. (11)	Electronic speckle pattern interferometry	Detection test capable of measuring • Tensile test • Fracture mechanics • Bending tests • Thermal expansion	Moderate field of view (200 x 300 mm^2). Difficulty with smaller field of view to measure deformation and defects around the narrow groove weld.
Laser Optical Engineering (12)	Shearography	Detection test capable of measuring • Delamination • Disbonds • Impact damage • Thermal and mechanical loading	Difficult to adapt with lower field of view requirements of narrow groove weld measurements.
Optonor (13)	Shearography and holographic system	Detection test capable of measuring • Delamination • Impact damage • Liquid and gas inclusion • Cracks	Measuring narrow groove GTAW requires a smaller field view than this sensor is capable of measuring,
Laser Technology Inc (14)	Shearography	Detection test capable of measuring • Delamination • Disbands • Impact damage • Thermal mechanical loading • Porosity • Cracks	Current set up needs modification, to the extent of changing the camera and lens assembly to accommodate the requirements of measurement of narrow groove welds.
American Stress Technologies (10)	ESPI with hole drilling	Residual stress measurement with whole drilling.	Even though, this system has the field of view required for narrow groove weld measurements, this system is only capable of working in conjunction with an associated hole drilling unit. In order for this option to be used for dimensional weld measurements the hole drilling part would need to be detached and the software adapted accordingly.

2 Starting MRL/TRL level

The current TRL and MRL is 1 as this system is getting developed from its first principles. The justification for these values is shown in Appendix 1.

3 Overview of technical challenge for industry

3.1 Evolution from first principles

ESPI has been used for measurement of deformation in the laboratory for more than a decade. It is only in recent years that commercial sensors have appeared for industrial use (Table 1-1) (10) (11). Each of these systems are quite narrowly focused on dealing with particular industrial challenges. For example: the prism system developed by American Stress Technologies can only be used for residual stress measurement when drilling holes (10). Such commercial systems do not provide sufficient levels of control so that they can be adapted to meet other industrial challenges.

ESPI is particularly sensitive to vibration and changes in alignment. Consequently when an ESPI sensor is being considered for alternative industrial uses it needs to be developed initially in the laboratory to prove that the measurement of the required deformation is feasible within that industrial context before a suitably-ruggedised sensor is developed for shop-floor deployment.

4 Development of experimental set up and the software

4.1 The setup

Depending on the type of measurement required, ESPI can operate in-plane (measuring deformation in the x-y direction, and out-of-plane (measuring deformation in the z direction). Consequently a system was designed which could easily be switched from in-plane measurement to out-of-plane measurement.

4.1.1 In-plane ESPI

Figure 4-1 shows the in plane displacement (displacement in x-y plane as shown in the co-ordinate in the figure) measurement setup using of ESPI. This is a typical dual beam illumination system where two beams illuminate the object simultaneously.

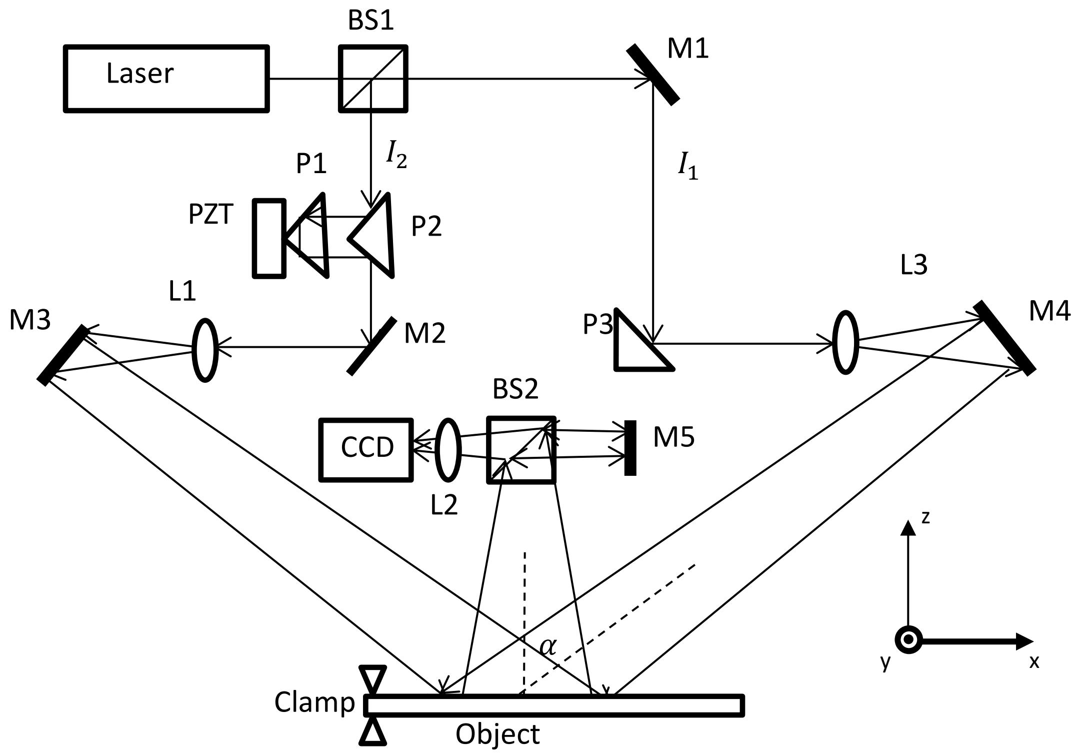


Figure 4-1: In-plane ESPI

The light from the laser source is divided into two parts. Illumination 1 (I_1) light is directed towards the object via the mirror M1 and prism P3 that is expanded to illuminate a specified area on the surface by the lens L3. The other part of the beam, illumination 2 (I_2) is transmitted through a displacement setup formed by prisms P1 and P2; the latter prism is connected to a closed loop piezo electric transducer (PZT) to provide the phase shifting mechanism. The beam is then guided towards the object with the help of mirror M2, lens L1 and mirror M3.

Both the wavefronts I_1 and I_2 are symmetrically inclined at an angle α to the surface normal to the object surface. Before the deformation, the object's surface is imaged by CCD camera with the help of mirror M5, beam splitter BS2 and lens L2. The scattered light from the illumination I_1 and I_2 form two separate speckle patterns which interfere in the image plane of the CCD camera and are recorded.

When the surface of the object is deformed, the speckle interferogram in the image plane of the CCD camera changes and is recorded. The phase due to the deformation is obtained by subtracting the phase calculated before deformation from the phase calculated after deformation as will be explained in more detail in section 4.3.

4.1.2 Out-of-plane ESPI

Figure 4-2 shows an ESPI setup for out-of-plane displacement (displacement in the z plane as shown in the co-ordinate in the figure). The light from the laser is split by the beam splitter BS1 into I_1 and I_2. Here I_1 acts as a reference beam and I_2 as the object beam, whereas in the in-plane configuration it is both beams that illuminate the object. The object beam I_1 is transmitted through the phase shifting assembly (P1 and P2) towards lens L1 to expand the beam. It is collimated on the object surface using the mirror M3. The diffused speckled light reflected by the object is collected and imaged on the CCD imaging plane. The reference beam I_2 is expanded and illuminates a ground glass plate, which is also imaged on to the CCD image plane. Thus, the speckle interferogram is formed on the CCD. Again the phase corresponding to deformation is measured by processing the phase shifted images (subtracting the measured phase before and after deformation), but this time it is for the deformation in the z direction.

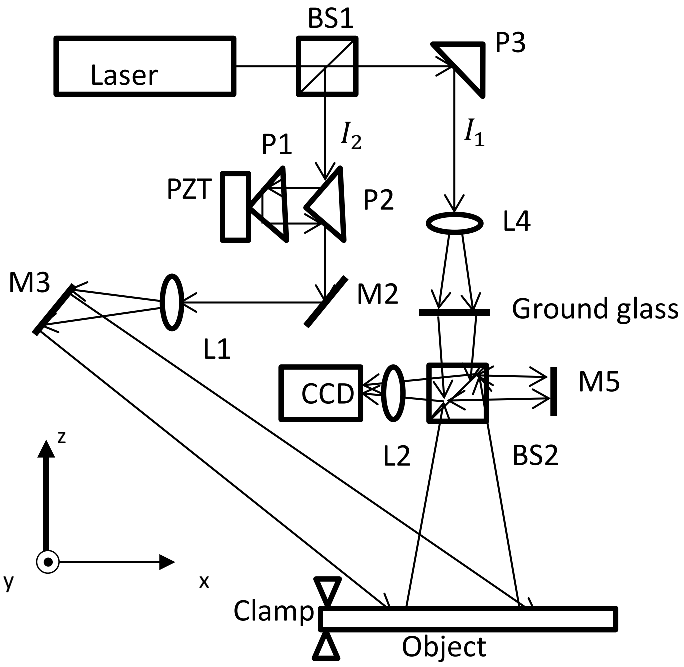


Figure 4-2: Out of plane ESPI

Comparison of the two setups above shows that they have a great degree of similarity (9) (15) and so a system was designed which could very quickly change configurations as measurement of both in-plane and out-of-plane deformations is required for the assessment of narrow groove welds.

Consequently the setup shown in in Figure 4-3 was designed. The difference between the in-plane and out-of-plane displacement measurement configuration is the position of the prism P3, which determines the reference illumination I_1's direction.

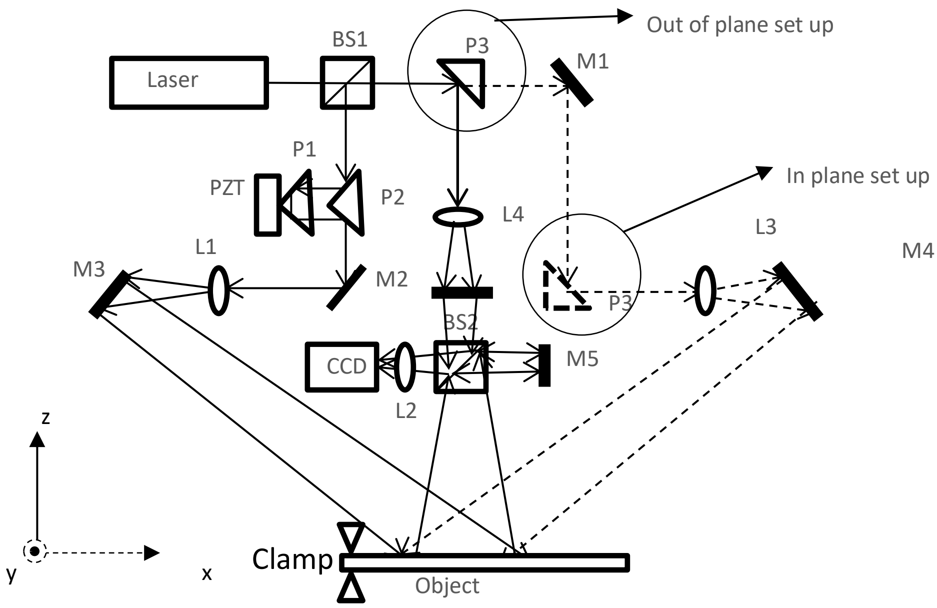
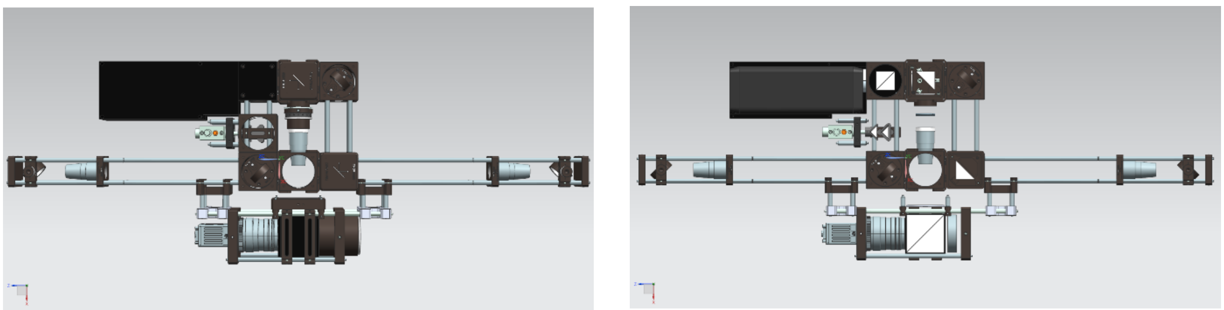


Figure 4-3: Integrated ESPI set up



(a) (b)

Figure 4-4: The ESPI unit (a) the top view, (b) the internal view

Figure 4-4 shows the final system with Figure 4-5 showing the light path for the in-plane configuration and Figure 4-6 the light path for the out-of-plane configuration.

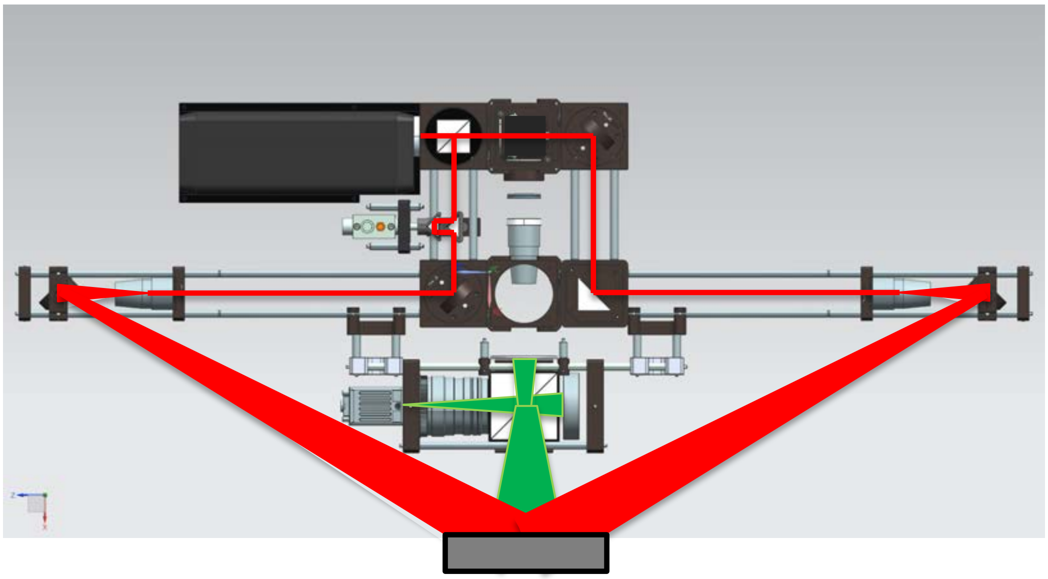


Figure 4-5: ESPI unit working in-plane mode

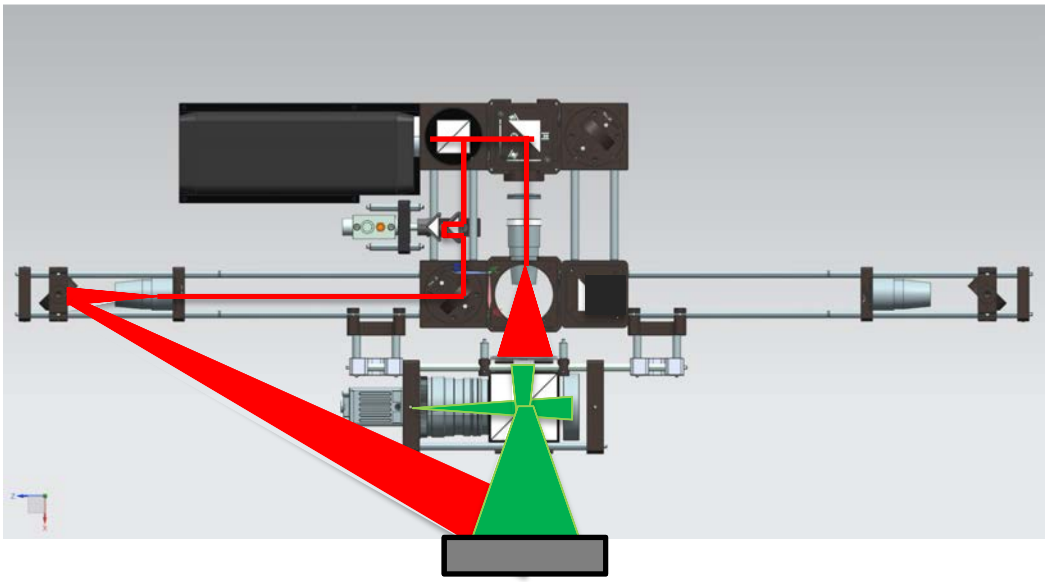


Figure 4-6: ESPI system out-of-plane mode

4.1.3 Off-the-shelf vs bespoke

Many of the required components were commercially available however the overall design was best achieved by iterative design and manufacture of 3D printed plastic components which are shown in Figure 4-7 and Figure 4-8

In order to make a compact set up, it is needed to have precise mounts for different optical components which are not commercially available. Hence, these particular mounts are designed and 3D printed.

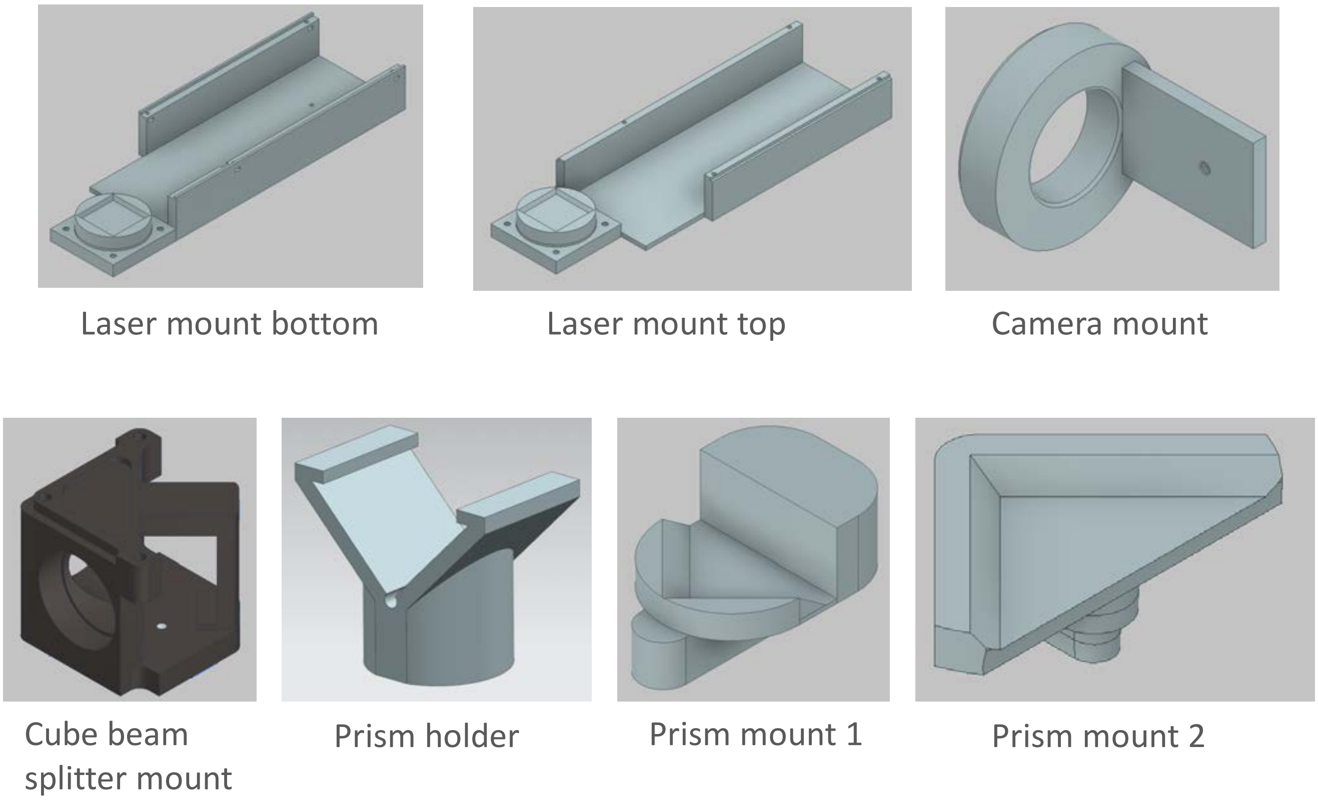


Figure 4-7: Example3D printed parts

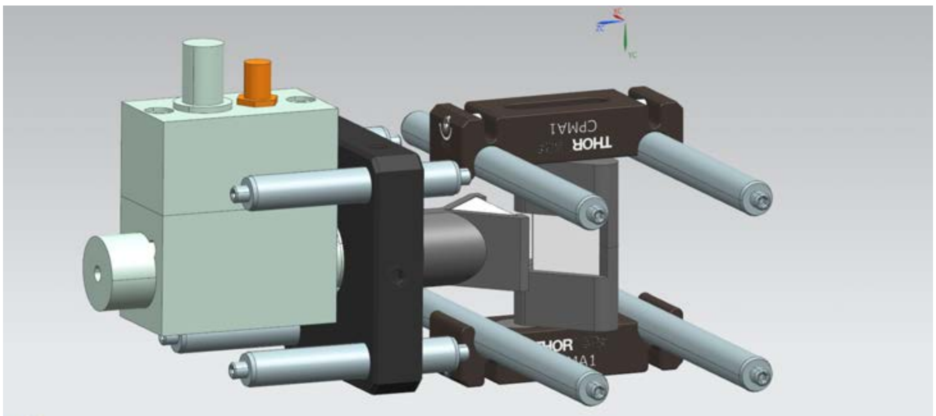


Figure 4-8: Attaching the prism to the PZT using 3D printed parts

4.2 Software

There are two stages to the software;

- Image acquisition.
- Image processing.

4.2.1 Image acquisition

Image acquisition comprises setting up the correct phase shifting and then capturing the phase shifted images before and after deformation. For this stage the phase-shifting PZT and the camera were synchronised using LabVIEW. The piezo crystal in the PZT expands with the application of a voltage which moves prism P1 by 158 nm, introducing the phase shift between I_1 and I_2. The PZT used in this work package in a closed loop PZT, which eliminates the need for calibration. The flowchart for this stage is shown in Figure 4-9 with Figure 4-10 showing the graphical user interface for the initialisation of the set up and the image acquisition window.

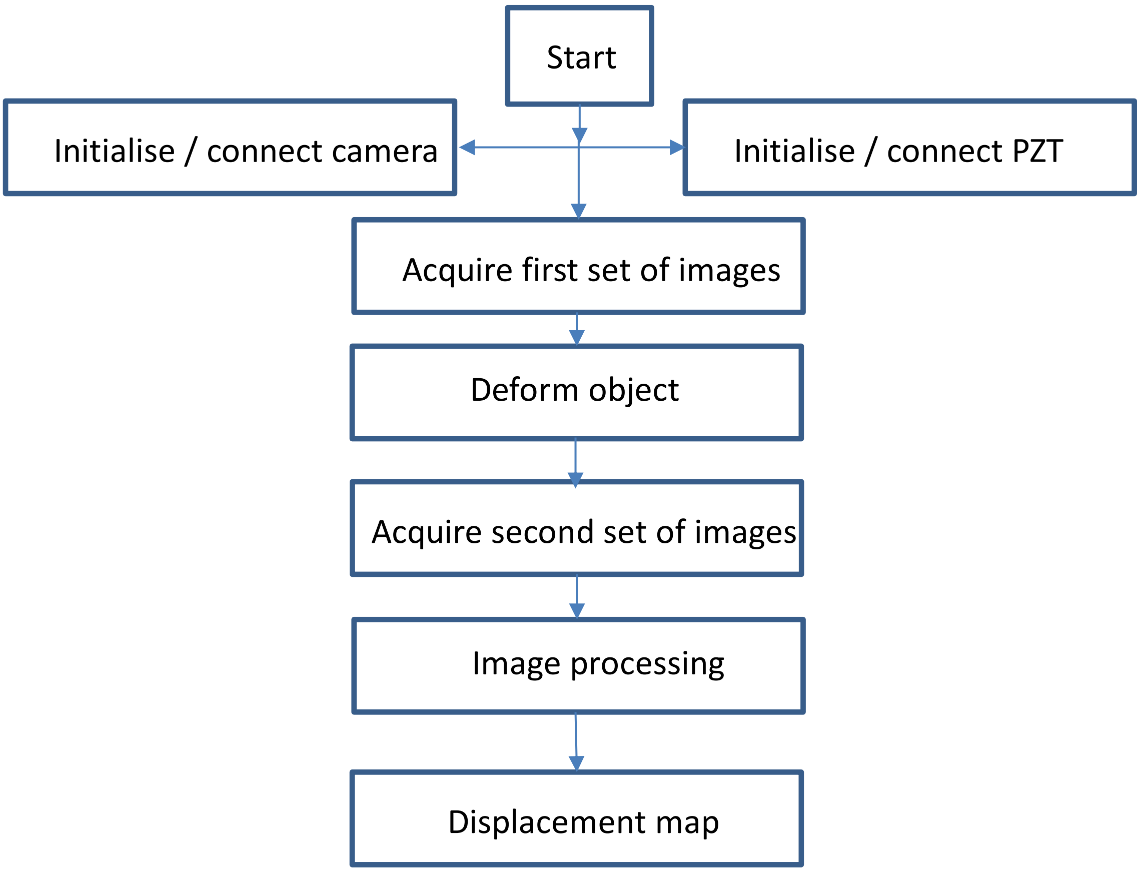
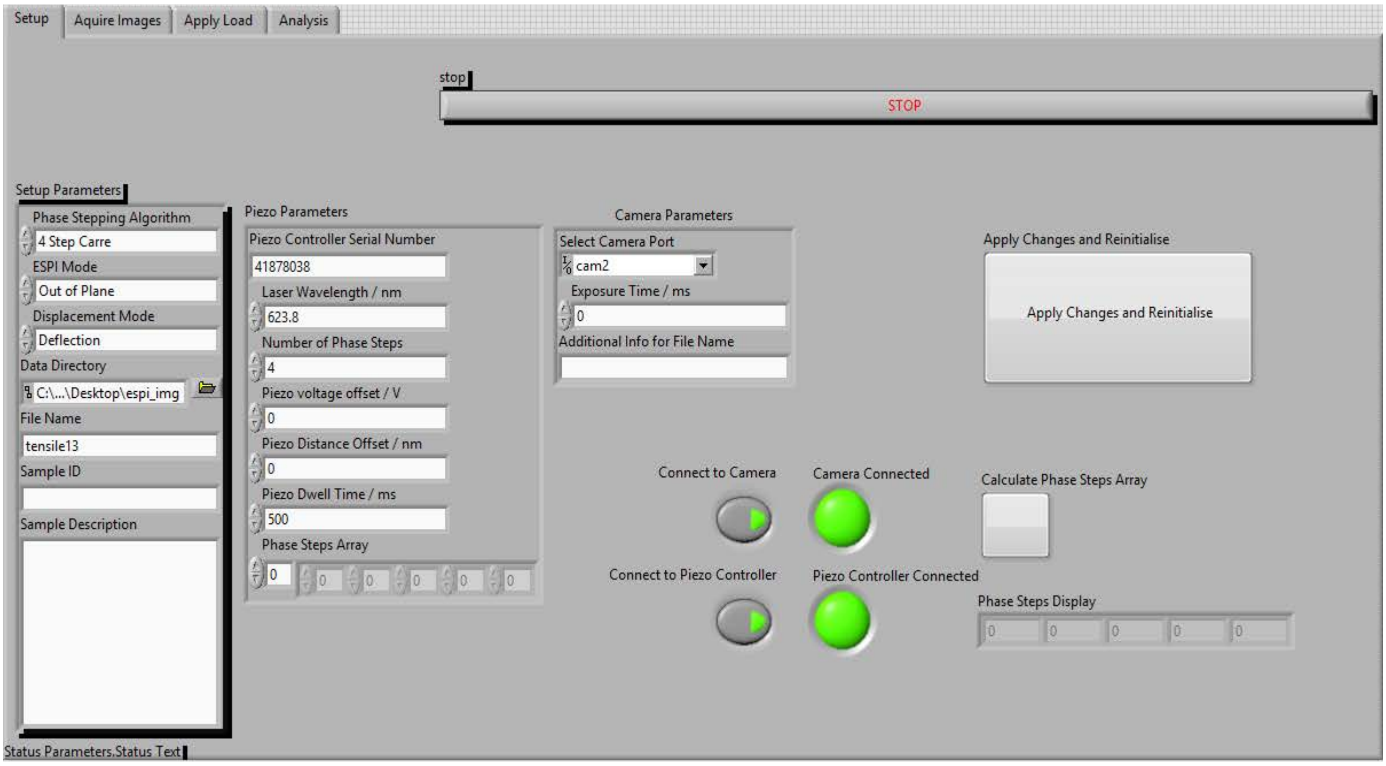


Figure 4-9: Flow chart of the image acquisition process



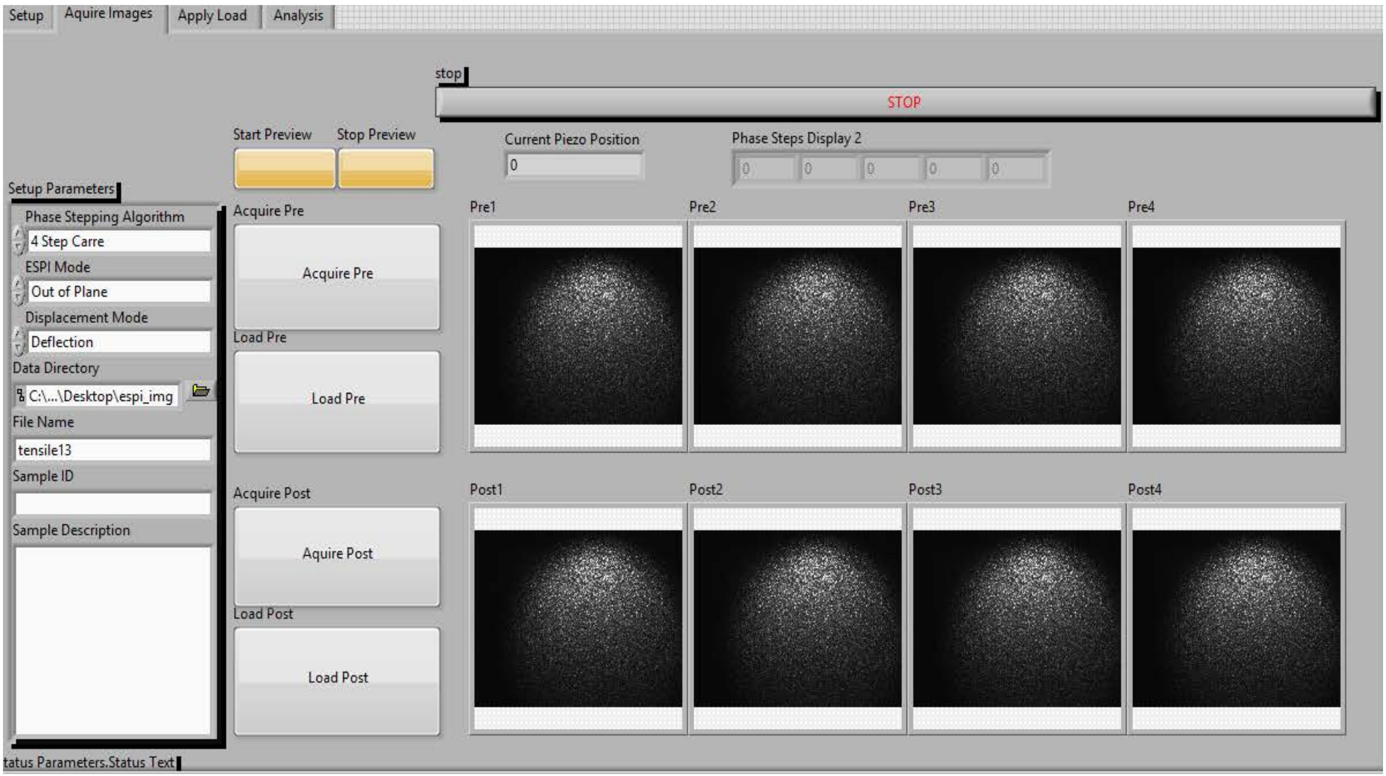


Figure 4-10: Screenshot of the software

4.2.2 Image processing

The second stage of the software undertakes image processing of the collected images. This stage was executed in MATLAB with the corresponding flowchart shown in Figure 4-11.

1. Load image: 4 phase shifted images corresponding to each state of the object is uploaded in the software.
2. Fourier transform: As we are dealing with speckle, there is a lot of high frequency background noise present in the image. In order to filter the high frequency noise, the image is Fourier transformed.
3. Filtering to reduce background noise: A low pass filter is applied to reduce the high frequency background noise.
4. Inverse Fourier transform: The filtered image is inverse Fourier transformed to obtain the phase information.
5. Crop to isolate the region of interest: If and when needed a specific region is cropped to focus on a particular region of interest.
6. Process all phase shifted images: Repeat steps 2-5 for all the images uploaded in step 1.
7. Calculate phase map: The phase due to deformation can be calculated from the processed phase shifted images. The set of phase shifted images due to interference of object and reference beam (I_1 and I_2 with a phase difference of $\Delta\emptyset_A$) is shown in equation 1-2 to 1-5. The phase shifted images after deformation can be written as below. After deformation (with introduced phase $\Delta\emptyset$ due to deformation) the recorded images, I_{1B}, I_{2B}, I_{3B}, I_{4B}

$$\boldsymbol{I_{1B} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\emptyset_A + \Delta\emptyset - 0) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\emptyset_A + \Delta\emptyset)} \quad \textbf{4-1}$$

$$\boldsymbol{I_{2A} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\Delta\emptyset_A + \Delta\emptyset - \frac{\pi}{2}\right) = I_1 + I_2 + 2\sqrt{I_1 I_2}\sin(\Delta\emptyset_A + \Delta\emptyset)} \quad \textbf{4-2}$$

$$\boldsymbol{I_{3A} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\emptyset_A + \Delta\emptyset - \pi) = I_1 + I_2 - 2\sqrt{I_1 I_2}\cos(\Delta\emptyset_A + \Delta\emptyset)} \quad \textbf{4-3}$$

$$\boldsymbol{I_{4A} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\Delta\emptyset_A + \Delta\emptyset - \frac{3\pi}{2}\right) = I_1 + I_2 - 2\sqrt{I_1 I_2}\sin(\Delta\emptyset_A + \Delta\emptyset)} \quad \textbf{4-4}$$

The calculated phase due to deformation is ($\Delta\emptyset$) is

$$\Delta\emptyset = (\Delta\emptyset_A + \Delta\emptyset) - (\Delta\emptyset_A) = \boldsymbol{\tan^{-1}\left(\frac{N_B}{D_B}\right) - \tan^{-1}\left(\frac{N_A}{D_A}\right)}$$

$$= \boldsymbol{\tan^{-1}\left\{\frac{N_B D_A - D_B N_A}{D_B D_A + N_B N_A}\right\}} \quad \textbf{4-5}$$

Where, $\boldsymbol{D_A = (I_{1A} - I_{3A})}$, $\boldsymbol{N_A = (I_{4A} - I_{2A})}$, $\boldsymbol{D_B = (I_{1B} - I_{3B})}$ and $\boldsymbol{N_B = (I_{4B} - I_{2B})}$.

As the deformation and phase is directly proportional, the deformation d can be calculated from the phase and wavelength of the light λ

$$\boldsymbol{d} = \Delta\emptyset \frac{\lambda}{2\pi} \tag{4-6}$$

In this case $\lambda = 0.632$µm, so, $d = 0.1\ \Delta\emptyset$

8. Unwrap phase map (if needed): If the phase variation in the object is more than 2π, the phase gets wrapped around the measured phase. In this situation, the phase is retrieved by unwrapping.

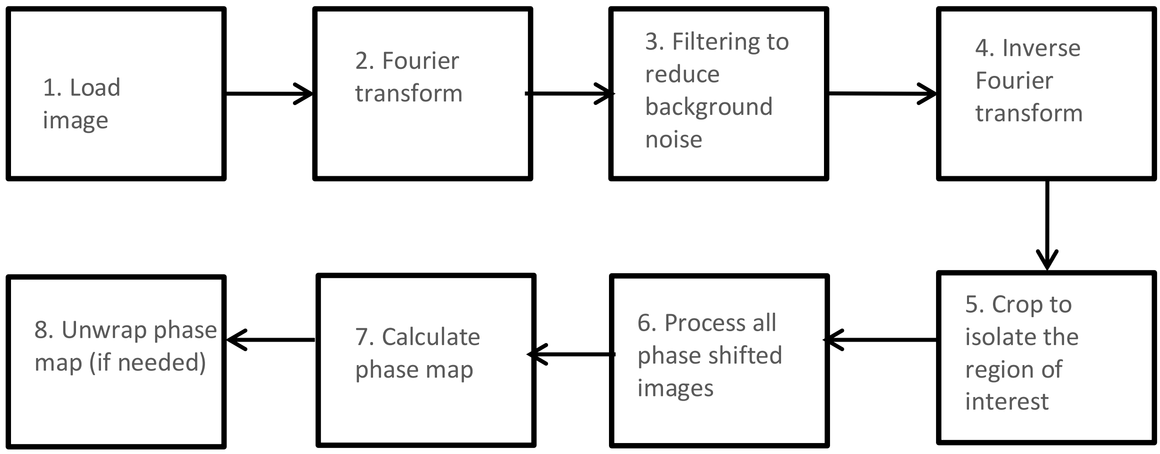
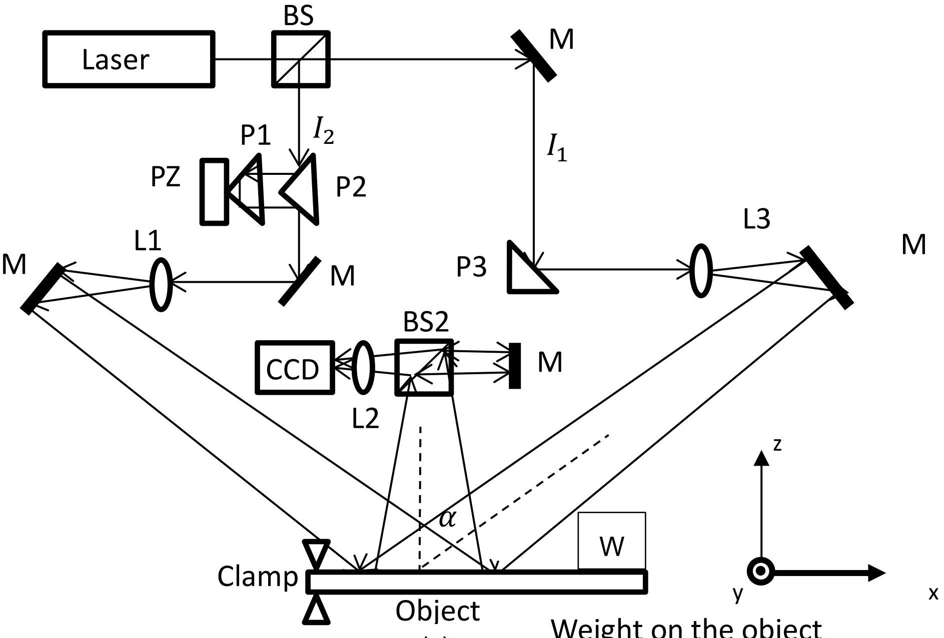


Figure 4-11: Schematic of the image processing.

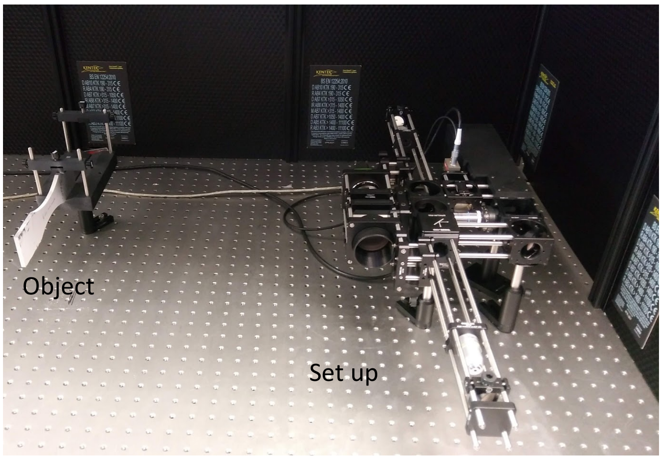
The two different coding platforms were used on this occasion to play to their respective strengths and enable rapid and agile development of the system. LabVIEW was used for driving the PZT and camera due to its strength in integration of physical hardware, whereas MATLAB's in-built library was used for post-processing the images. It is recommended that any future work, once the hardware and software requirements are fully specified, should be carried out on one of these packages throughout the system and all code is ported to the selected package.

4.3 Feasibility results

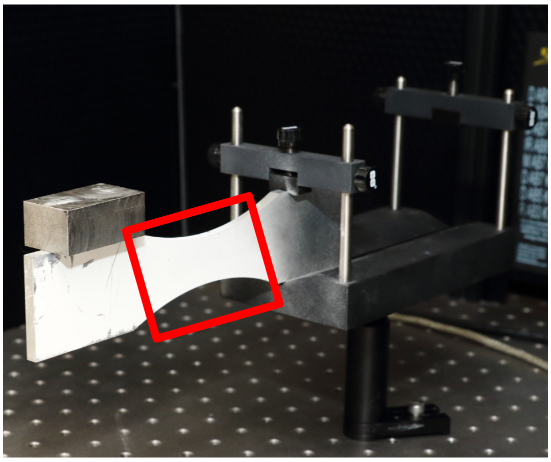
The primary feasibility test result for in-plane measurement from the eight phase shifted images calculated from before and after deformation. The schematic of the setup is shown in Figure 4-12(a). An aluminium dog-bone artefact is clamped at one end and a weight W is placed on the other, causing it to have an in-plane displacement. The experimental set up of the same is shown in Figure 4-12(b).



(a)



(b)



(c)

Figure 4-12: (a) Schematic and (b) experimental set up of in-plane displacement measurement. (c) Object with load

An aluminium dog-bone artefact (object Figure 4-12(c)) was used to validate the in plane detection capability of the set up. A weight of 240 g was placed on the object (shown in Figure 4-12(c)) and corresponding 'before' and 'after' speckle patterns of the object were recorded. The camera field of view is shown by the red box.

The phase is calculated corresponding to the phase shifted images before deformation and shown in Figure 4-13(a). As the field of view is quite large, the phase information can be drowned by the background noise. For phase measurement and calculation, a part of the object is selected as shown in Figure 4-13(b). The phase after the application of the load W is shown in Figure 4-13(c). The resultant deformation is calculated according to equation 4-9 and 4-10 and shown in Figure 4-13(d). The change in the deformation due to application of load is clearly visible in Figure 4-13(d) and is within a total range of 0.3 µm.

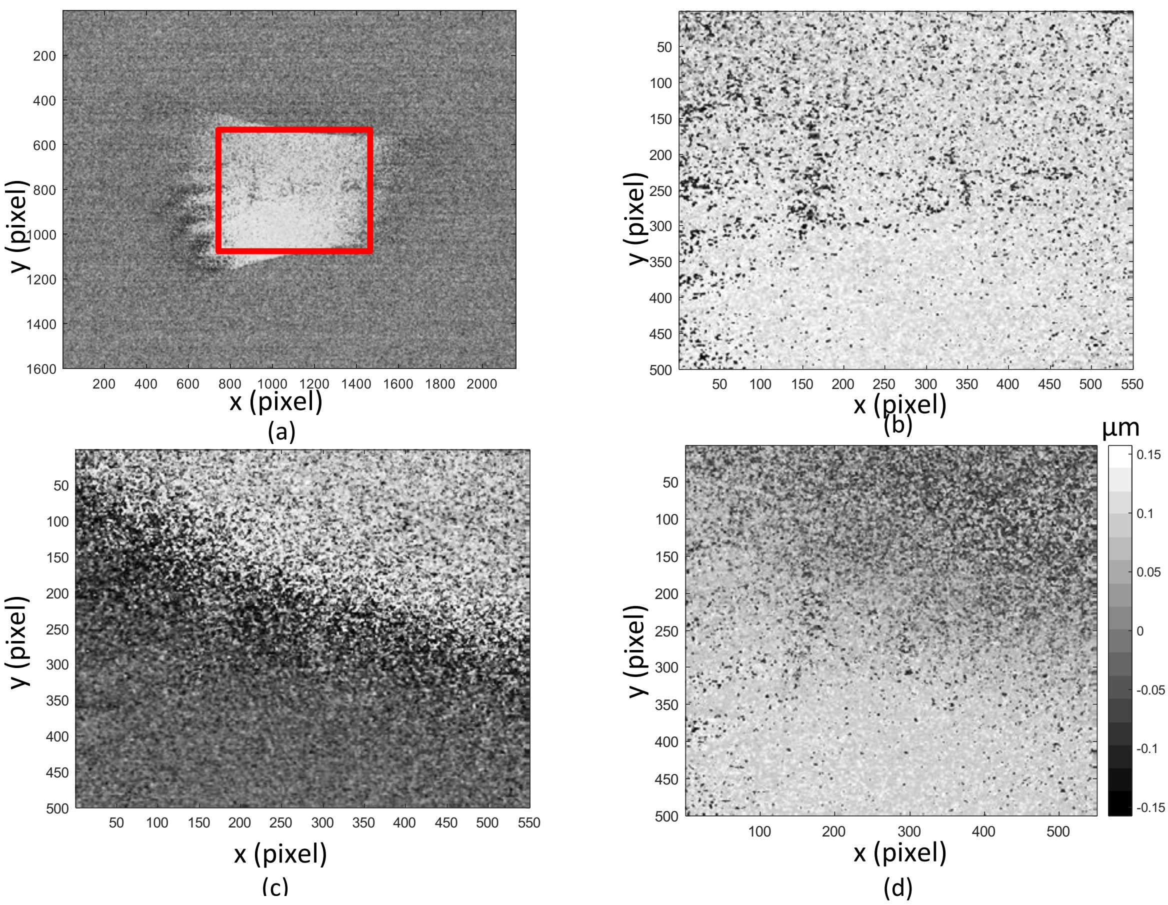


Figure 4-13: (a) Calculated phase before loading (b) Zoomed in image of the red box in (a) (c) Calculated phase after the load was applied (d) Deformation due to load

This system is developed to show the potential of ESPI technique as well as for a feasibility study. Both the software and hardware of the system need further development in order to use it as a standalone directly deployable industry ready system. Along with that, to exploit full advantages of this technique the following improvement needs to be done (as a future work)

1. The integration of the image processing software with the image accusation software in a single software platform.
2. A noise reduction and averaging software needs to be designed to supress and minimise the noise components.
3. A polariser or neutral density filter needs to be included in the out of plane set up to reduce the intensity of the reference beam and make the measurement possible.

5 Conclusions and further work

5.1 Final MRL/TRL level

When completed the finished TRL of this work package was 2. The justification for these values is shown in Appendix 1.

5.2 Potential industrial impact

By the very inclusion of this technique in the SIMPLE project as the 'emerging sensor technology' work package, the exact industrial impact of ESPI in narrow groove GTAW is yet to be fully determined. The sensor is seeking to measure deformation in real time in the order of hundreds of nanometres and so is 80-100 times more sensitive than the next nearest commercially-available measurement technology. This high resolution measurement of deformation will be extremely beneficial in terms of extrapolating surface residual stress information and spotting defects in the very early stage of manufacturing. The alternative low resolution surface measurement instruments used for a similar purpose, tend to miss these high resolution defects which can potentially result in the failure of the components.

If this surface residual stress information can be captured at the point of manufacture in a low cost, non-destructive methodology the information will be of extreme utility. Potential applications include;

- Quantified residual stress measurement for stress corrosion cracking in stainless steel components.
- Non-uniform stress fields to use as defect detection during manufacture (this envisaged application).
- New applications for in-service inspection.
- Validation and verification of computer models and provision of data for qualification tests and digital twins.

The primary significance of the development of this system in the work carried out in this project is that it has the flexibility to adapt to a wide variety of measuring scenarios when compared to commercially-available off-the-shelf sensors. It can quickly change from in-plane to out-of-plane measurement. With introduction of a zoom lens the system will have the potential to change the field of view from 5 cm x 5 cm to 1 m x 1 m. This system has strong potential for application in the nuclear sector, for its adaptability of high resolution deformation and potential for stress measurement over a low as well as high field of view.

5.3 Future work

The current system has only been deployed in the laboratory. It is able to detect the change in deformation, however it needs further development to exploit the full potential of the system.

- Iterate on the current set up add out of plane functionality.
- Include an adjustable zoom lens in order to control and extend the field of view.
- Design software to reduce the speckle related noise.
- Integration of the image acquisition, phase shifting and image processing in a single software platform

Along with that, from performance point view, the following needed to be done to validate the measurement.

- Calibration of the system as well as repeatability and reproducibility check of the results.
- Validation of the results with other existing well established commercially available measurement techniques.

The above mentioned work will be able to demonstrate the full potential of the system. In order to deploy the set up as a versatile standalone system in the factory surrounding it requires

- Development of the ESPI technique for measuring nanometre-scale deformation in subtractive and additive manufacturing techniques and understanding their performance implications.
- Miniaturising and ruggedising the sensor so that it is capable of successful deployment in a factory environment; either standalone or incorporated into a multi-sensor system such as SIMPLE.

5.4 Route to industrial adoption

While this sensor has successfully demonstrated that non-contact nanometre deformation can be measured in the laboratory, it is still at a considerably low TRL/MRL. Industrial adoption will require more research that is focused towards making the system capable of operating in a workshop environment.

A possible route for industry adoption would be:

1. Demonstrating the versatility of the system by measuring welded and machined parts, and comparing the results with the commercially available systems.
2. Identify potential commercial and/or academic partners to collaborate for funding to extend the research which can deploy the application in industry.

References

1. **Hecht, Eugene.** *Optics.* s.l. : Addison Wesley 997, 1998.

2. **Schreiber, Horst, and John H. Bruning.** Phase shifting interferometry. *Optical Shop Testing.* 2006.

3. **K, Creath.** Phase-measurement interferometry techniques. [book auth.] E. Wolf Ed. *Progress in Optics Vol. XXVI.* Amsterdam : Elsevier Science Publishers, 1988.

4. *Speckle pattern and holographic techniques in engineering metrology.* **Butters, J. N. & Leendertz, J. A.** s.l. : Opt. Laser Technol. 3, 1971.

5. *SpeckleSense: Fast, Precise, Low-cost and Compact Motion Sensing using Laser Speckle.* **Zizka .J, Olwal. A, Raskar R.** Santa Barbara, CA, USA : UIST'11, 2011.

6. *Applications of 3D speckle interferometry to material and component testing.* **Ettemeyer, A., Wang, Z. & Walz, T.** s.l. : Opt. Insp. Micromeasurements II , 1997.

7. *Electronic speckle pattern interferometry (ESPI).* **Sharp, B.** s.l. : Optics and lasers in engineering, Elsevier, 1989.

8. *Strain measurement by three-dimensional electronic speckle pattern interferometry: potentials, limitations, and applications.* **Ettemeyer, A.** s.l. : Optical Engineering, Vol. 42.

9. *Development of the integrated measuring system of strain distribution and defect using ESPI & shearography.* **Kim, H.-J., Gweon, D.-G. and Kim, H.-C.** 11, s.l. : International Journal of Precision Engineering and Manufacturing, 2012, Vol. 13.

10. **Stresstech.** [Online] [Cited: 25 July 2019.] https://www.stresstech.com/en/products/prism/#.

11. **Dantec Dynamics.** [Online] [Cited: 25 July 2019.] https://www.dantecdynamics.com/3d-espi-system-q-300.

12. **Laser Optical Ltd.** [Online] [Cited: 25 July 2019.] http://laseroptical.co.uk/wp-content/uploads/2015/08/Defect-Dtect-Factsheet-.pdf.

13. **Optonor.** [Online] [Cited: 25 July 2019.] https://optonor.com/Userfiles/Upload/files/OPTONOR_SNT410.pdf.

14. **Laser techology inc.** [Online] [Cited: 25 July 2019.] http://www.laserndt.com/products/pdf/LTI-2100M_DS_101813r1.pdf.

15. *A simple design for an electronic speckle pattern interferometer.* **Moore, T. R.** s.l. : American Journal of Physics , 2004, Vol. 72.

16. **4D technology.** [Online] [Cited: 25 July 2019.] https://www.4dinspec.com/products/4d-inspec/.

I. System Integration

SIMPLE System Integration Work Package 2.3 Final Report

for

Nuclear Advanced Manufacturing Research Centre

R/155144-11-3 NI1032

30/05/2019

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Executive summary

- The objective of work package 2.3 System Integration involves building a demonstrator system, integrating sensor technologies from concurrent work packages into a narrow gap welding process.
- The technical motivation for the System Integration work package is:
    - Capturing, storing and displaying analogue signals, digital signals, camera images and 3D data recorded during the welding process provides the opportunity for data from traditionally disparate systems to be combined, potentially improving detection of welding quality issues.
    - Providing a sensor agnostic data capture platform has scope for applications in other areas of the manufacturing process.
- The advantages of the SIMPLE core system:
    - Use of many commercial off the shelf hardware and software components, based around an existing data acquisition platform along with some software integration. This approach allows the core system to be close to industry-ready.
    - Expandable, flexible and rugged hardware can be distributed around large and complex machinery.
    - Processing power capable of running machine learning algorithms live.
- Technical challenges
    - Synchronising and storing different sensor data types, i.e. video, voltage and current.
    - Relating recorded data to a physical position on the workpiece.
    - The harsh operating environment with high electrical noise required changes to the system design.
- Development path
    - Requirements Capture
    - Requirements Assessment and Market Research
    - System Design, Layout & Bill of Materials
    - Integration, Challenges and Resolutions
    - Testing
- Potential industrial impact
    - The system could be used as a template to develop an automated inspection system, provided the sensor data translates reliably to a quality indication of the weld
    - The SIMPLE platform is not specific to narrow gap welding, or indeed, welding. There are a wide range of potential applications which could benefit from high-speed data acquisition from multiple sensors

AMRC

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1 Systems Integration

1.1 Technical Challenge and First Principles

1.1.1 The Problem

The SIMPLE project aims to integrate a range of machining, fabrication and inspection operations onto a single manufacturing platform.

The Advanced Manufacturing Research Centre (AMRC) Design and Prototyping Group (DPG) are one of the partner organisations in the Nuclear AMRC consortium delivering the SIMPLE project.

The DPG's project objective is WP2.3 - Systems integration. Effectively, this involves building the demonstrator system, which will require the integration of selected sensor technologies with the welding hardware and software. The system:

- Will allow for recording, analysing and exporting various data types (analogue, video, 3D).
- Is designed around requirements of various sensor work packages, with scalability for the future.
- Targets synchronised capture of required welding data, with a close-to-industry platform, which could potentially be developed into a final product.

The SIMPLE project involves several sensor technologies, handled by multiple partners in discrete work packages. The work packages with sensor technology comprising of:

- 3D line Profile Sensors.
- High-frequency Input and Output Power Monitoring.
- Vision System – High Dynamic Range Welding Camera.
- Acoustic Sensors – High Bandwidth Microphones.

This phase of the SIMPLE work will focus on developing the core process monitoring functionality. This system will be specified and implemented with the consideration that this may need to facilitate real-time analytics and closed-loop control in the future.

There are additional sensor technologies in the broader project, which, due to their low technology readiness level (TRL), were not intended to be integrated during this phase.

1.1.2 Summary of Similar Solutions and Technology

The final system will have several sensors fitted around the welding head of an industrial welding unit. The data from the sensor is then to be captured and stored in a time synchronised format. The recorded data will then be made available in various export formats for analysis, as well as being viewable in a graphical user interface.

1.2 Start MRL/TRL Level

The starting TRL level of the integrated SIMPLE system is TRL2.

The starting MRL level of the integrated SIMPLE system is MRL2.

The justification for these values is shown in Appendix 1.

1.3 Overview of Technical Challenge for Industry

1.3.1 Evolution from First Principles

This sub-section contains a summary of each sensor, and its critical challenges, broken down per work package, as well as broader considerations regarding the general process.

1.3.2 Laser Sensor Work Package

The 3D work package utilises two laser line profile sensors, which require synchronising and post-processing into a single profile. The selected cameras are Micro-Epsilon Gap Control units. The camera captures 3D line profiles and transfers them via Ethernet, with several options of Ethernet communication standard (1).

The laser sensors use a custom Ethernet data structure, which requires software to be developed to interpret the data into the desired format.

In addition to the laser profile scanners from micro-epsilon, investigations were made into the integration of a low-cost thermal imager from the same vendor. After some initial study, it was decided to continue development due to limited options for integration and automated control, as well as challenges in gathering accurate thermographic data.

1.3.3 Acoustic Work Package

The acoustic work package specifies two channels of analogue data with a sample rate of 200 kHz at 24-bit resolution, one per microphone, connected via their IEPE (Integrated Electronics Piezo-Electric) interface. These microphones can provide information about the sensor to the capture device automatically, via the Transducer Electronic Data Sheet (TEDS) standard, making it effectively “Plug and Play” (2). As such, the data acquisition (DAQ) system should preferably support TEDS also.

The sample rate and resolution required by the specified GRAS microphones are beyond the capability of many hardware platforms, limiting the choice of hardware and software at the core of the project.

The position of the microphone leads to long analogue cable lengths, which increases the susceptibility to electrical noise, subsequently degrading signal quality. Changes to the design topology of the data acquisition system were required to minimise this.

1.3.4 The University of Sheffield (UoS) High-frequency Input and Output Power Monitoring

The output voltage and current signals are digital to analogue conversion from the UoS Physics teams interface electronics. They require two analogue channels with 200 kHz sample rate at 24-bit resolution, with a range of 0-10 V.

The input power monitoring consists of recording three voltage and current lines of a three-phase supply, with the potential to also monitor neutral to earth voltage and current. Monitoring input power requires four analogue channels of +/- 500 V minimum range, that can match or exceed that of the existing offline Fluke 434 power analyser, which is capable of sampling at 200 kHz with 16-bit resolution (3). Additionally, another four low voltage analogue channels are required, with suitable current transducers for the current range (up to 60 A) to convert the current through the machine input into a low voltage signal.

The high data speed limits the hardware choices available for the core system, ruling out some platforms and hardware which do not have sufficient speed.

The existing UoS hardware is used to send analogue signals to the additional SIMPLE system hardware, similar to the acoustic work package (1.3.3) analogue cable lengths need to be kept to a minimum to ensure signal integrity.

1.3.5 TWI Vision System Work Package

The TWI vision system uses a Xiris XVC-1000 camera to acquire high dynamic range images of the weld. The camera transfers images via a 1 Gbps Ethernet connection (4). The system then processes the recorded images with a machine learning algorithm. The machine learning algorithm utilises NVidia's CUDA platform. "CUDA® is a parallel computing platform and programming model developed by NVIDIA for general computing on graphical processing units (GPUs). With CUDA, developers are able to dramatically speed up computing applications by harnessing the power of GPUs" (5).

The non-standard and proprietary interface utilised by the camera required additional software to be developed in order to integrate and control the camera.

Generally, camera images can have significantly high data rates, stressing hard disk speed and capacity.

1.3.6 General Welding and Process Specific Considerations

The SIMPLE system needs to synchronise the data recorded from each sensor with all other data sources, but more fundamentally, the data also needs to be related to physical position on the workpiece. Recording position information ensures any results derived by the sensors can be associated with the defect area on the workpiece. For analogue data, the system converts this to a high-resolution digital signal for storage. For already digital signals, for example, camera images, the system converts them to a preferred format for storage.

1.4 Work Conducted and the Development Path

1.4.1 Requirements Capture

As previously outlined in Section 1.3.1, the first step of the development plan was to carry out a requirements capture phase, gathering information to build a system specification.

With the key interfaces and data types from the specified sensors known, the process of selecting a hardware and software platform for acquiring and storing the data could begin.

1.4.2 Requirements Assessment and Market Research

Throughout the specification and design of the SIMPLE integration system, industry-ready, commercial of the shelf components were selected wherever possible, simplifying the potential route to commercialisation, reducing risk and increasing TRL and MRL.

The analogue signal requirements dictated that some form of voltage data acquisition system was necessary. Typically, specialist hardware is needed to handle the precise timing and low noise requirements of analogue signals. While there are options from numerous vendors in this area, the specific sensor requirements did narrow potential solutions. The chosen platform had to be capable of handling a 200 kHz sample rate at 24-bit resolution with both low and high voltage signals, as well as being available in a rugged chassis suitable for locations such as welding workshops.

In addition to acquiring analogue data, the overall system had to capture and display the 3D scan data, and monochrome images from the Xiris camera, synchronised alongside the analogue data to provide context between each data stream. The Xiris SDK is proprietary and requires a Windows-based computer to control the camera and acquire images.

The data acquisition platform would also ideally integrate with Windows 10, to allow us to combine all of the sensor requirements into one system.

From our earlier deductions, we considered several hardware solutions from vendors of data acquisition equipment. National Instruments cDAQ platform offered a rugged platform; however, could not achieve the data speeds required.

National Instruments PXI chassis or PCI-e add-in cards have sufficient speeds, but not in the package required. Indeed, offerings from Dewetron and HBM did not offer the correct combination of bandwidth, resolution and electrical isolation like the chosen platform from Dewesoft. Additional to this, the high voltage inputs of the Sirius units are also safety rated to CAT III 600 V; CAT II 1000 V (6). A catalogue extract of the Dewesoft Sirius units, with a selection of sensor interfaces listed (Figure 1-1) shows the diversity of sensor interfaces available.

Figure 1-1: Extract from catalogue page for Dewesoft Sirius

1.4.3 System Design, Layout & Bill of Materials

With the core platform selected, specifying the components and layout of the system could commence. A system topology diagram was designed, starting with choosing the interface hardware and secondary components required for connecting the external equipment to the DAQ system, (Figure 1-2).

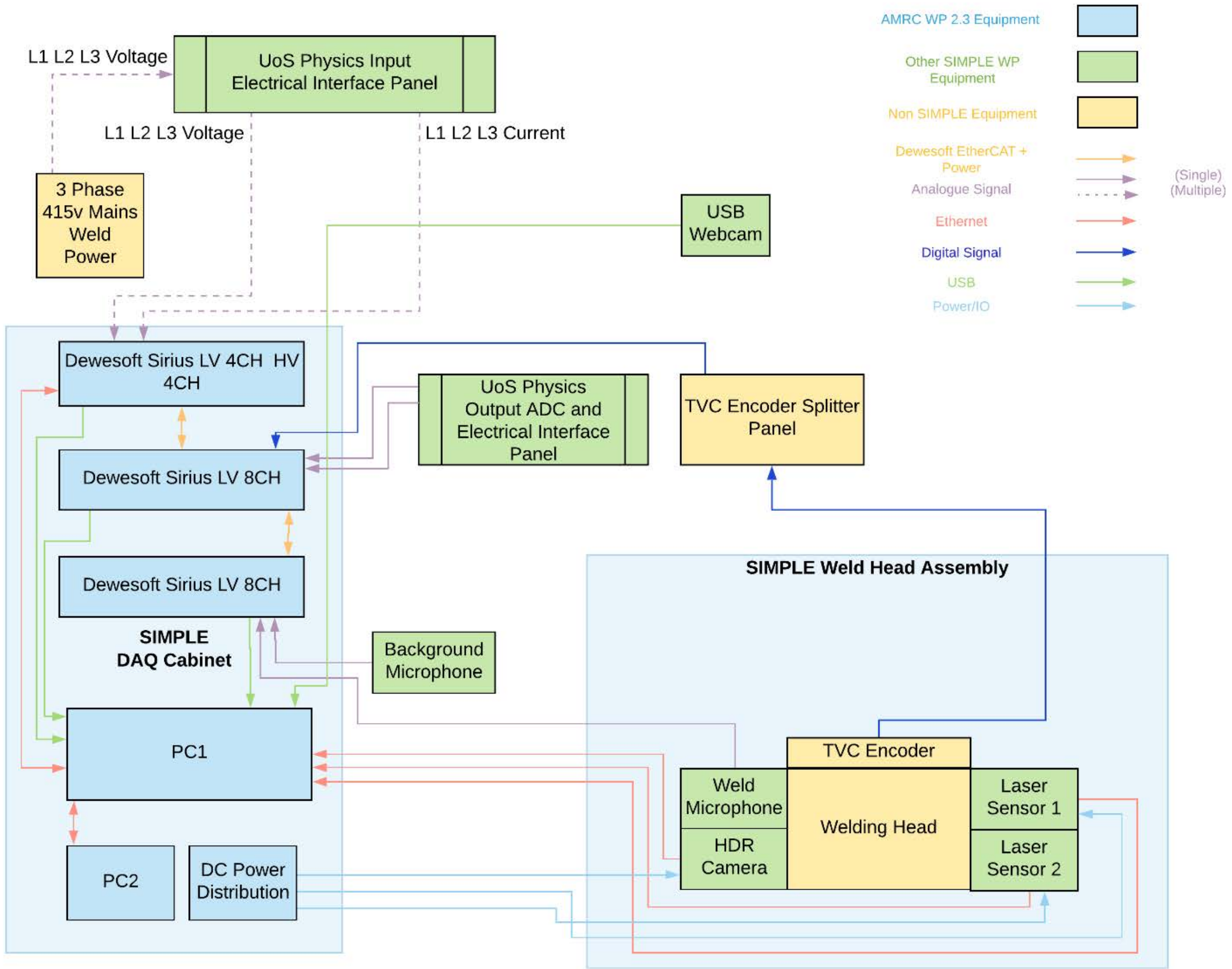

Figure 1-2: Original system topology diagram with a centralised DAQ system

Now, with the system hardware specified, an electrical bill of materials was produced, along with a finalised electrical design and layout.

The main panel of the SIMPLE system was selected as a 42u 19" rackmount system; using a rackmount panel allowed for a large number of IT-based components to be housed and connected using the equipment from the IT industry. To accommodate some of the electrical components used for digital inputs, outputs and power to the sensors, a section at the rear of the IT cabinet is fitted with panel mounted DIN-rail, for easy use with electrical standard terminals and components.

1.4.4 Integration, Challenges and Resolutions

Figure 1-3: Image of the main SIMPLE cabinet build pre-shipping (rear view)

Figure 1-4: Image of the main SIMPLE cabinet build pre-shipping (front view)

Construction of the system then commenced. The build phase lasted approximately three months for the main panel. The completed enclosure in its pre-shipping state is visible in Figure 1-3 and Figure 1-4. After the build of the main SIMPLE cabinet at the design and prototyping workshop, the system was transported across the AMRC campus to the Nuclear AMRC building and positioned near the Polysoude system in the arc welding bay (Figure 1-5).

Sensors mounted on the weld head require the cable run spans the length of the welder and some floor space to reach the main SIMPLE cabinet. In addition to the already long signal path, accommodating for the movement of the boom arm is cause for extra cable length acting as strain relief. Cabling in and around the pre-existing installation was a significant challenge. Combinations of plastic and metal cable trunking were used to offer some protection to the more fragile data cables running to the sensor equipment.

With the sensors connected and external wiring completed, the installation team carried out post assembly checks, powered on the system for the first time on location. Once the assembled and installed system passed the commissioning, initial welding trials could commence.

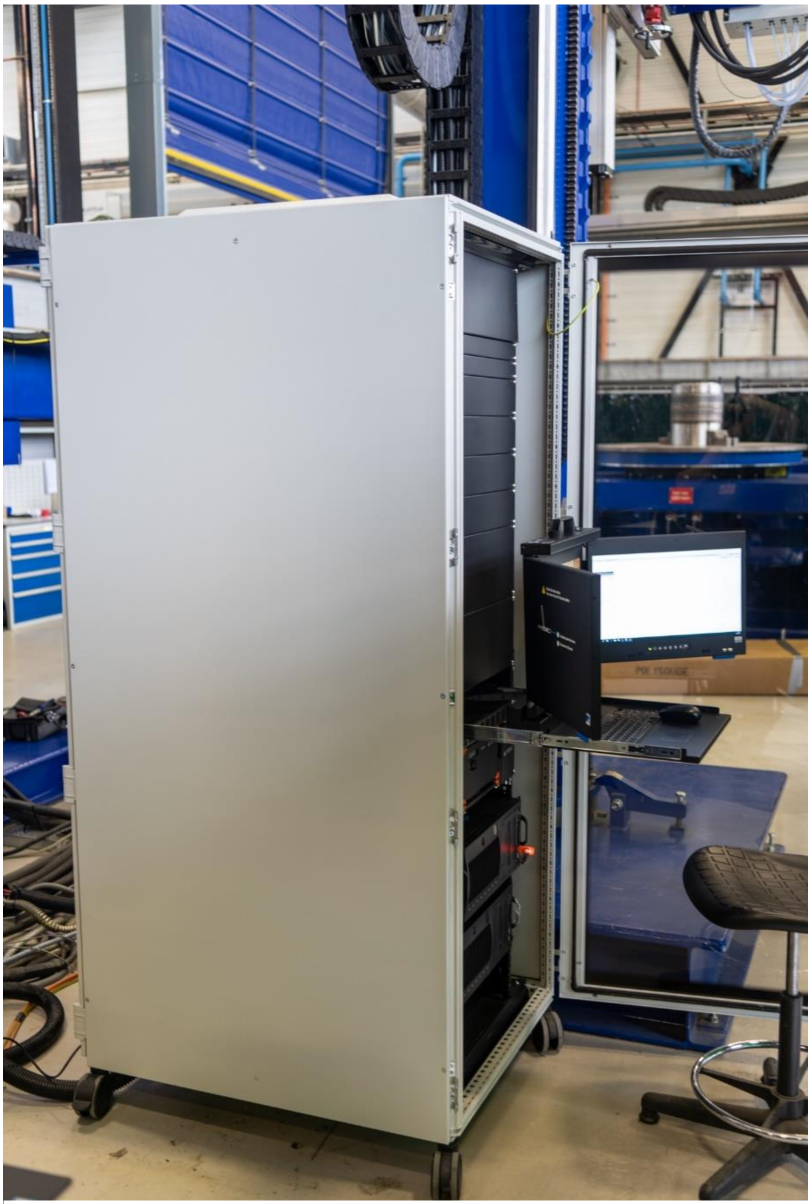

Figure 1-5: Image of the main SIMPLE enclosure as installed on the arc welding bay (front left view)

Following the initial weld trials, the work package teams raised the issue of long cable; the significant analogue cable runs carrying the audio signal from the weld, and background microphones to the DAQ unit in the main cabinet were susceptible to the Electro-Magnetic Interference (EMI) emitted by the welding process. After discussions with the team, the decision was made to move the DAQ analogue to digital hardware near to the weld head. By extending the digital connection between the DAQ hardware and the PC, the noise immunity of digital signals can be exploited to benefit the overall signal integrity. In the selection process, we had already identified rugged, electrically isolated characteristics of the Dewesoft Sirius units, giving confidence they can operate in such an environment.

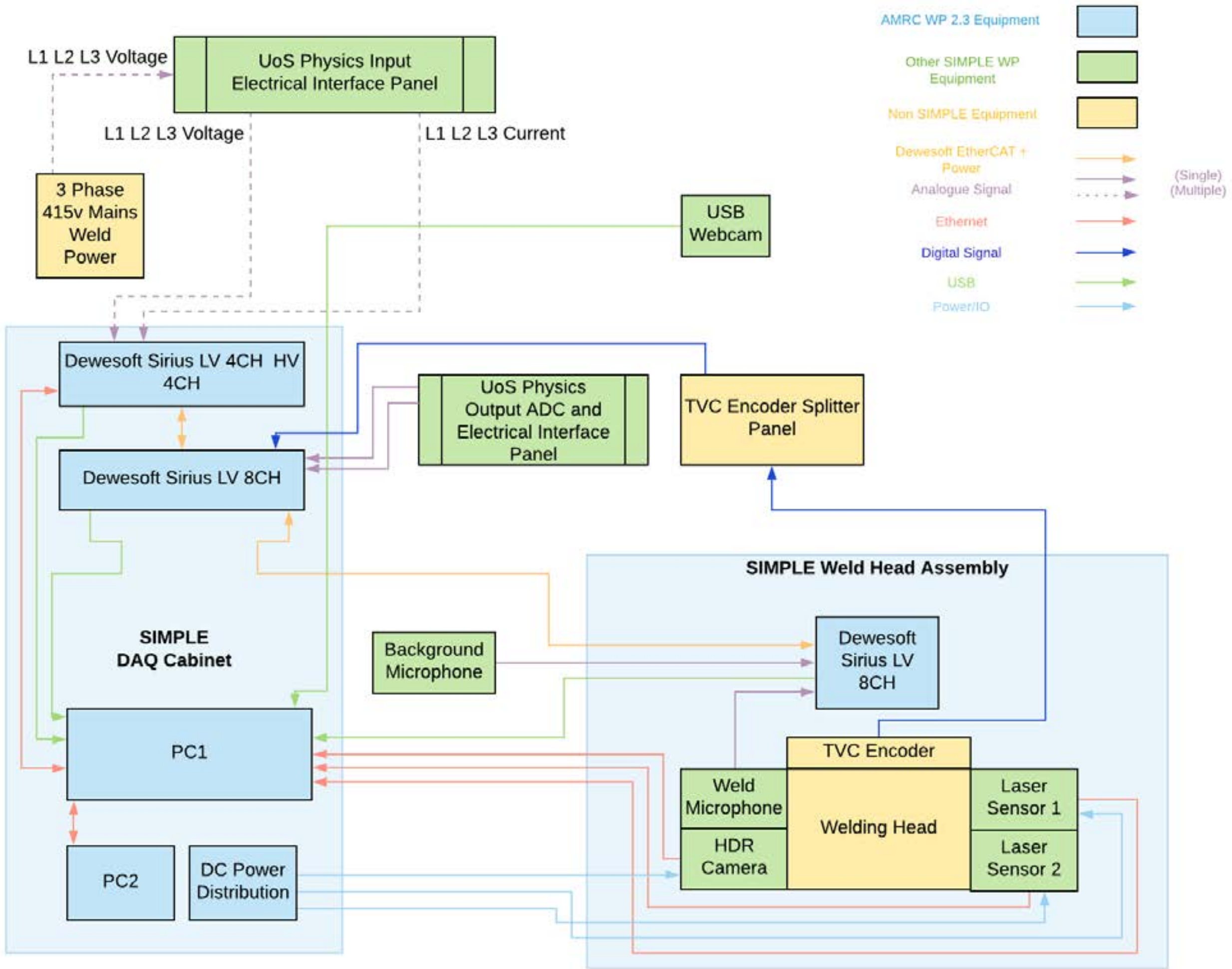

Figure 1-6: Updated system topology diagram with a DAQ unit moved from the main cabinet to the weld head

To relocate the DAQ unit to the weld head requires passing a USB cable (green line in Figure 1-6) and the Dewesoft proprietary EtherCAT cable (red line in Figure 1-6) from the SIMPLE DAQ cabinet to the newly positioned Dewesoft LV fitted to the weld head. The changes in topology in Figure 1-6 bring the analogue to digital conversion much earlier in the signal chain. The microphone data now travels the majority of the distance as a much more noise resistance digital signal.

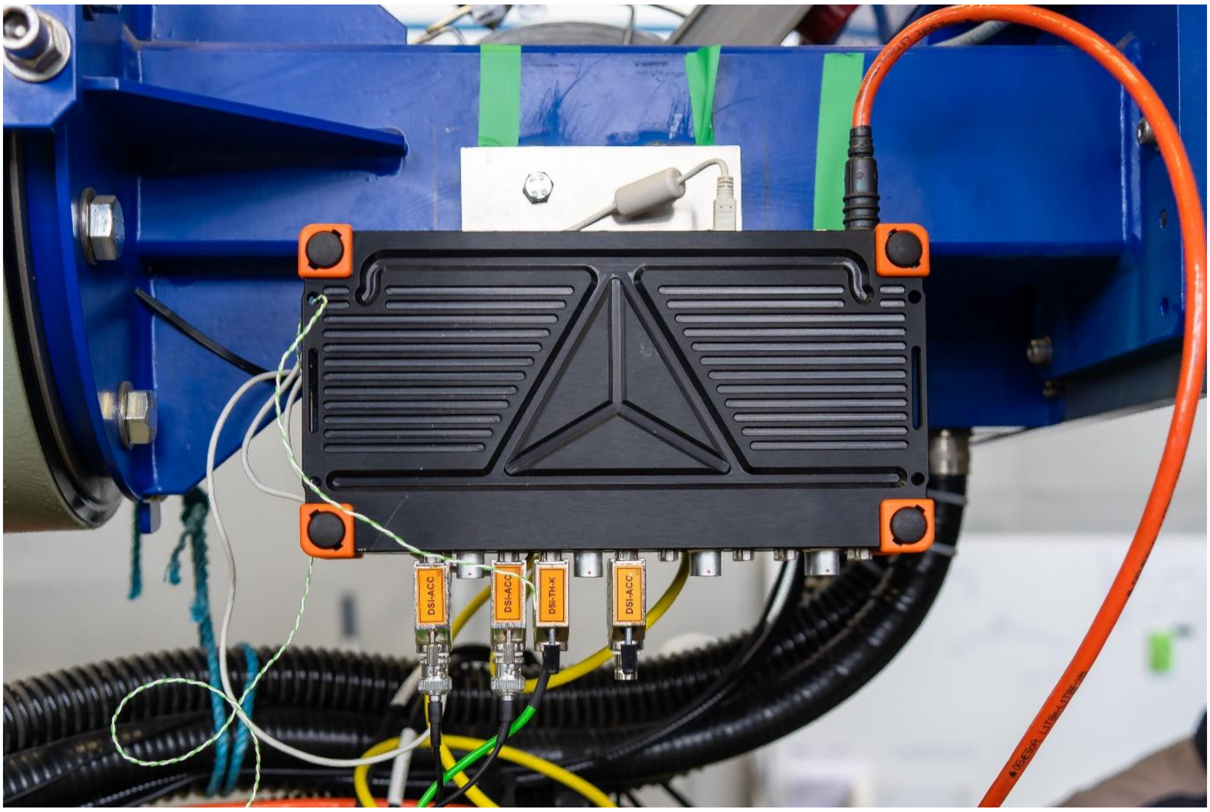

Figure 1-7: Image of the DAQ unit placed near the head of the boom arm, used to capture microphone and temperature data

The modification was then carried out; the physical device mounted to the welding boom arm is visible in Figure 1-7.

Continuing the installation and commissioning process of the system, subsequently, the UoS Physics process monitoring team's hardware was delivered to site. Similar to the microphones, the analogue signals between the physics team's electrical input panel and the main SIMPLE cabinet where a cause of concern, particularly the length of the cables. The placement of the two electrical enclosures was dictated by location to power sources, clearance for personnel, moving parts and access to the system already installed on the area. The decision was made to move the DAQ unit responsible for input power next to the UoS work package's input power monitoring hardware. The new topology diagram (Figure 1-8) shows the new cabling requirements, and position of the input power DAQ unit situated near the power source.

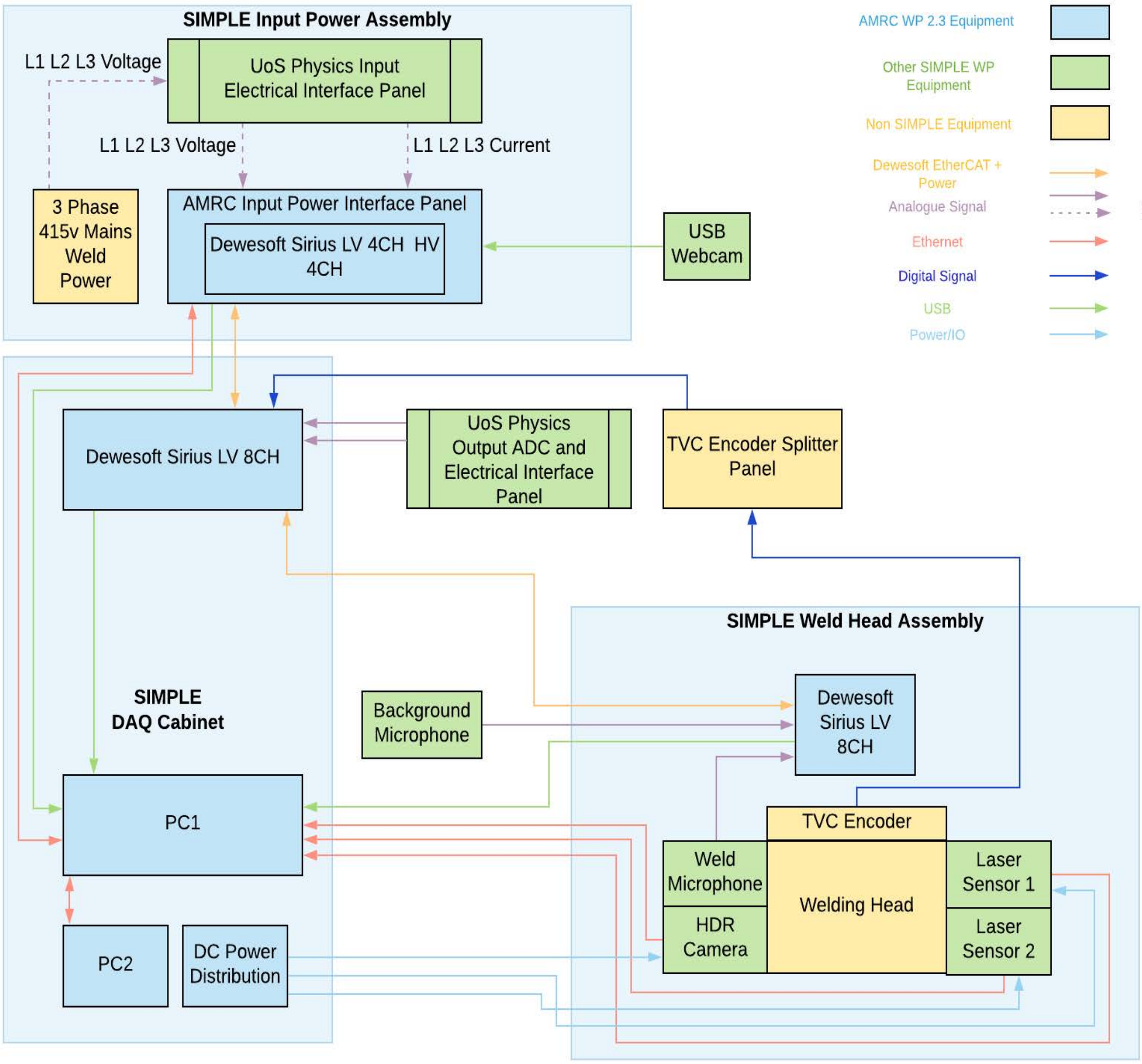

Figure 1-8: Diagram of final DAQ system topology with the input power DAQ relocated

To house the hardware external to the main cabinet, a small enclosure housing the required components was built, represented as 'AMRC Input Power Interface Panel' in Figure 1-8. The constructed and installed unit visible in the photograph in Figure 1-9 (the smaller grey enclosure atop the larger UoS panel).

Figure 1-9: Image of the input power monitoring DAQ enclosure (top) with the UoS electrical interface panel (bottom) in situ at the arc welding bay

The changes made in Figure 1-8 conclude the modifications to the original design and forms the final topology of the SIMPLE system.

1.4.5 Testing

With the installation of the hardware complete, the system hardware was now ready to commence welding trials. In Figure 1-10, the Human Machine Interface (HMI) of the SIMPLE system is visible, after capturing data from a weld pass. The left panel is displaying the image from the TWI vision system camera, through Xiris weld studio. The centre screen is the main Dewesoft capture screen, responsible for recording the analogue signals, the position feedback and the video feed of the welding bay. The right screen displays the data from the 3D camera, recorded using the manufacturers own software.

Figure 1-11 shows some of the sensors fitted to the weld head, for context.

Figure 1-10: Image of the SIMPLE panel's HMI post welding

Figure 1-11: Image of the weld head used for the SIMPLE trials

Dewesoft's X3 software displays the recorded analogue data (Figure 1-12). Alongside the raw signals captured by the software, the system calculates power data live, along with other mathematical functions.

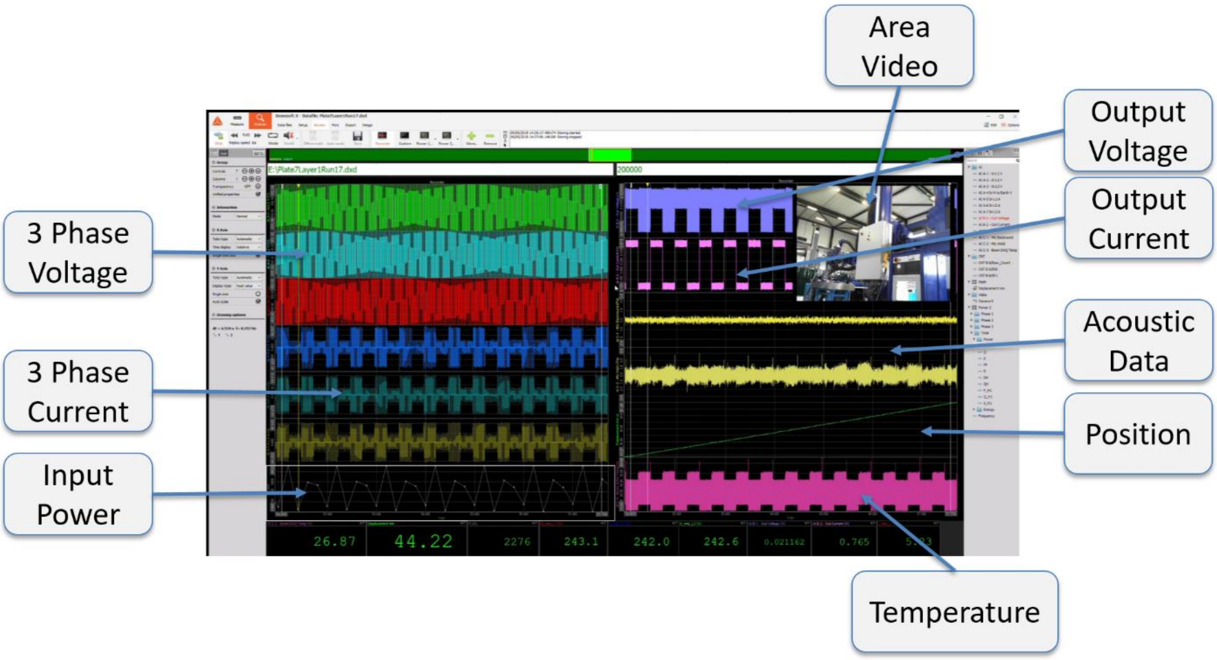

Figure 1-12: Screen capture of the primary data acquisition screen, with each data type captioned

1.5 End TRL/MRL Level

The ending TRL at the end of the project for the integrated SIMPLE system was TRL4.

The ending MRL at the end of the project for the integrated SIMPLE system was MRL3, meeting many of the criteria for MRL4.

The justification for these values is given in Appendix 1.

1.6 Potential Industrial Impact

Results drive the successful adoption of any automated inspection system. For the SIMPLE system to provide a quality or time benefit, the sensor data and algorithms need to provide a proven means of detecting welding quality issues as they happen. Moreover, such a system needs to take action to correct the fault automatically, or, prevent work continuing until the welding technician rectifies the issue.

Once there is a combination of sensors and technologies that can achieve this, the platform that they exist within becomes somewhat secondary. There is, however, added value in having a platform that can evolve with the needs of the end-user. One of the key strengths of the approach taken for the SIMPLE system is the context many individual systems provide when the data is available to process collectively.

1.7 Future Work

1.7.1 Additional Sensors

The powerful high-speed DAQ platform we have developed has the potential to be expanded to include novel or existing sensor technologies not currently used in this project phase, e.g. Ultrasonic.

1.7.2 Machine Learning on Gathered Data

The platform has significant GPU processing power, which could be utilised in future research to run machine learning algorithms, potentially in real-time. The data collected by the multitude of sensors could be processed with machine learning to provide improved predictions of quality and to optimise parameters.

1.7.3 Active Correction of Welding Parameters

The DAQ platform has the potential for real-time closed-loop process control. Using feedback in the welding process allows the SIMPLE system, with some integration work, to correct issues with quality detected by altering welding parameters. For example, the system could detect and adjust the position of the weld relative to the sidewall of the workpiece throughout the weld. Further to this, the Dewesoft platform has plugins to directly communicate with industrial programmable logic controllers (PLC), providing a convenient route of integration into existing machinery.

1.7.4 Live Processing of Vision System Images

The system could gather live classification data from the TWI vision system with some additional software layers. Custom software could be implemented to acquire images and control the camera, and automate the process of passing the image to the inspection algorithm and then receiving the classification data. The proposed software topology diagram Figure 1-13 outlines the layout of functions required for a potential live processing solution.

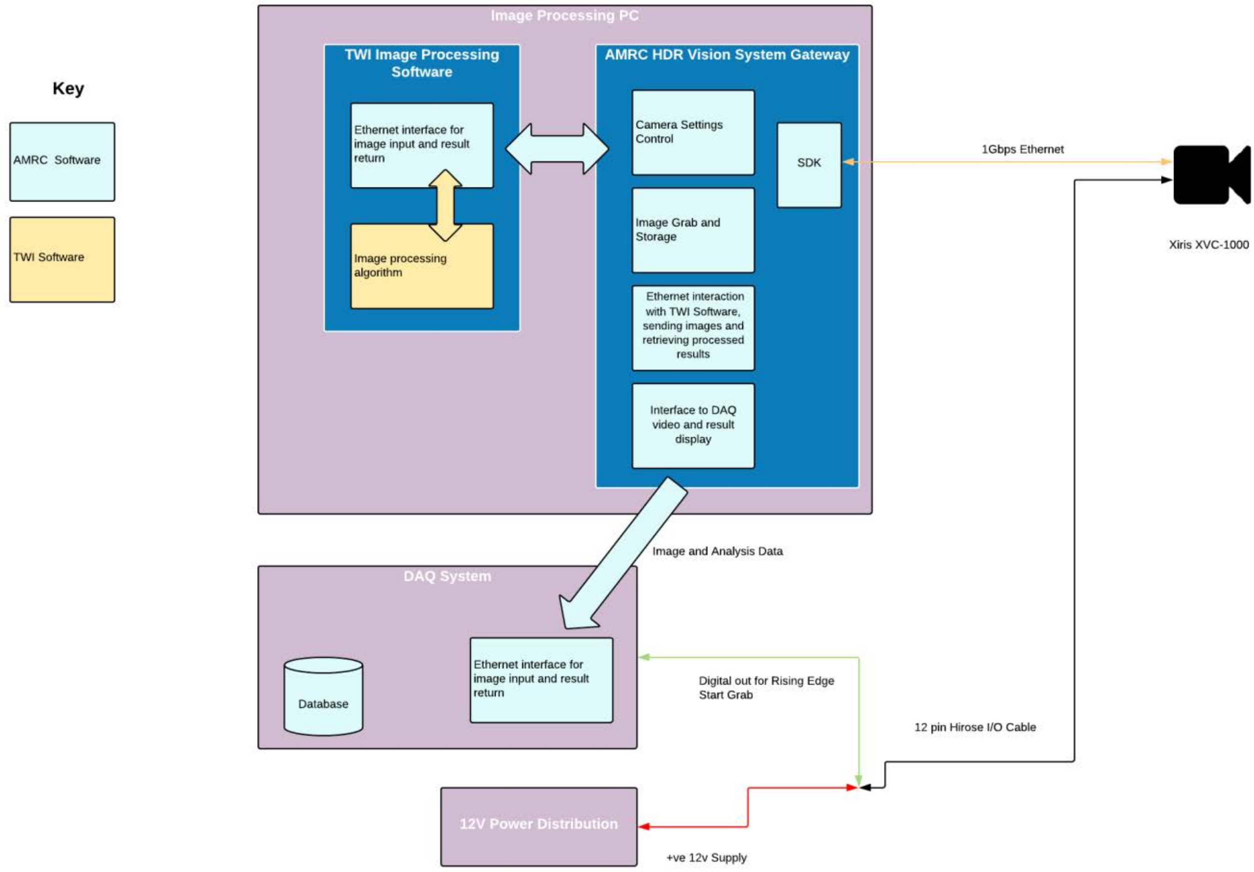

Figure 1-13: System topology diagram for live image processing of TWI vision system images

1.8 Recommendations for Further Research and Development

1.8.1 Route to Industrial Adoption

The hardware and software at the core of the SIMPLE system are already in full use across a wide variety of industries. The fundamental features of the SIMPLE platform lend themselves to any synchronised data acquisition and storage. The core hardware can support a wide range of sensors as standard, lending itself to use in many applications.

While CE marking and meeting regulatory conformance was outside the scope of this work package, creating a CE marked version of the SIMPLE system would be a relatively straight forward process. Some minor electrical design changes are required, along with Electromagnetic Compatibility (EMC) compliance testing. The specific nuclear industry regulatory requirements would have assessed on a per-application basis, but likely, these would require significant commitment in cost and time to achieve.

1.9 References

1. **Micro-Epsilon.** micro-epsilon.com scan control catalogue. *micro-epsilon.com.* [Online] [Cited: 01 August 2019.] https://www.micro-epsilon.co.uk/download/products/cat--scanCONTROL--en.pdf.

2. **G.R.A.S.** GRAS.dk Teds Description Page. *GRAS.dk.* [Online] G.R.A.S. [Cited: 2019 07 17.] https://www.gras.dk/teds.

3. **Fluke.** *Fluke.com.* [Online] [Cited: 01 August 2019.] https://dam-assets.fluke.com/s3fs-public/F430-II_umeng0100.pdf.

4. **Xiris.** Xiris XVC-1000 Datasheet. *Hubspot.net.* [Online] [Cited: 01 August 2018.] https://cdn2.hubspot.net/hubfs/206970/Datasheets/Letter%20Datasheets/Xiris_XVC-1000-1100_Datasheet.pdf.

5. **Nvidia.** Nvidia CUDA Developer Zone. *Nvidia.com.* [Online] Nvidia. [Cited: 17 07 2019.] https://developer.nvidia.com/cuda-zone.

6. **Dewesoft.** Sirius Technical Specification. *Dewesoft.com.* [Online] [Cited: 01 08 2019.] https://dewesoft.com/products/daq-systems/sirius/tech-specs.

J. Demonstrator

Single Manufacturing Platform Environment (SIMPLE) - Stage 2

Demonstrator

NI1032-REP-06

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Project report

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Executive summary

- The objective of the demonstrator work package is to demonstrate the integrated sensor system on an industrially relevant use-case.
- The baseline use-case for the demonstrator technology is that of thick section pressure vessel welding applications. The selected application was as follows;
    - Narrow groove gas tungsten arc welding of thicknesses up to 50mm.
    - SA508 Grade 3 class II steel.
    - J-weld preparations specified to ISO 9692.
    - Welding carried out on Nuclear AMRC's Polysoude NG-8-300 welding cell.
- The technical demonstration of this application included;
    - Synchronised continuous data collection of the:
        - Laser profile scanners.
        - Acoustic sensors.
        - Vision sensor system.
        - Power monitoring system.
    - Real time display of the outputs of these sensor sources.
    - Deposition of known flaws in the workpiece for correlation to real time data.
- In addition, the ultrasonic sensor system demonstrated the collection of intermittent in-process data during welding, successfully detecting a lack of fusion defect.
- Further work to deploy the technology will need to include:
    - Application of the welding technology to a representative scale component
    - Development of the near to real time detection algorithms
    - Development of industrially acceptable process control systems

Contents

1 Technical challenge and first principles

The aim of the SIMPLE demonstrator is to:

- Integrate advanced digital sensing technologies into one synchronous system.
- Deploy state-of-the-art analysis methods capable of identifying features in the data that correlate to welding imperfections.
- Demonstrate this technology on industrially relevant welding equipment and applications.
- Have future capability to feedback the outputs of this analysis to the operator/welding equipment control system.
- Demonstrate data interoperability and the benefits of data-rich manufacturing systems

1.1 The problem

The size of the components found nuclear manufacturing dictate that large column and boom based welding systems are required. Due to the orientation of the welding process, narrow geometry of the weld preparation and physical distance from the arc the operator has few direct methods to monitor the process. Consequently, the operator has to use remote monitoring methods and these are quite limited in their scope.

The SIMPLE project's purpose is to develop a suite of sensing technologies to enhance the in-process monitoring of thick section mechanised arc welding. In addition to the individual sensor development, the project demonstrator is to bring these sensors into one integrated system to enable multiple sensor signals to be analysed in parallel and close to real-time. This will enable correlations between data and welding imperfections to be established.

The scope of this work package is to demonstrate this integrated weld monitoring system gathering real-time, synchronised, in-process data in a representative welding application and prove the concept for seeding the data with imperfections for the system to detect. It is the scope of future work to develop the analysis methods for correlating this data to the welding imperfections.

1.2 The vision

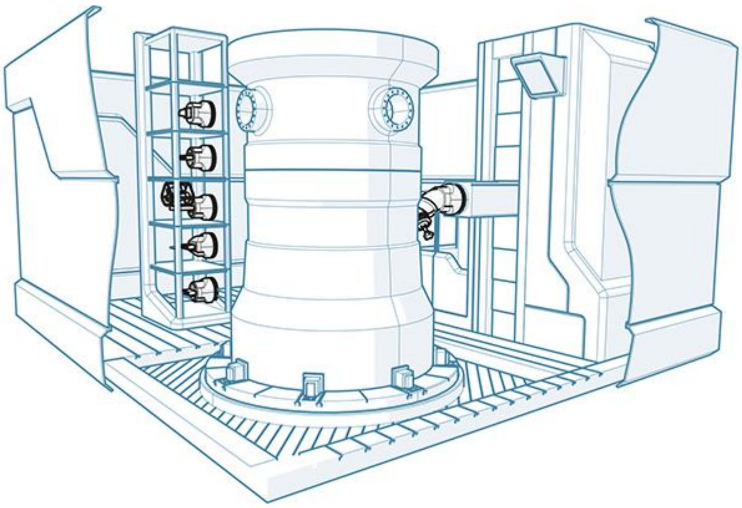

Figure 1-1: The vision for the SIMPLE platform. An integrated assembly and welding stage involving many sensors

The overarching aim of the SIMPLE platform is to automate the machining, assembly, welding and inspection of large pressure vessels and other high integrity/value components. This will reduce operator dependency, and as this is done on a single platform, will reduce both the safety risks and the risks arising from part movement. To demonstrate this feasibility of this concept within the time frame available to this project, an arc welding process was selected. Arc welding provides an opportunity to investigate a process that has many input variables and potentially rich data sources if they can be successfully recorded and analysed. To reduce the operator dependency and to automate the mechanised arc welding process the confidence in any automated system must be incredibly high. To develop and automate the control of the welding system the analysis methods must be fed large quantities of data to verify and validate the control algorithms.

The initial step towards this vision is the development of a data capturing system capable of detecting the welding conditions that correlate to the welding imperfections which require mitigating actions to be undertaken. Once this system is developed and validated, it can be used to provide additional information to the operator as to the quality of the welding process, as well as capturing the manual interventions carried out by the operator. As the analysis system is developed the quality of the feedback given to the operator will increase, ideally to the point where the semi-automated system is suggesting the optimal welding conditions to the operator. The ultimate goal is that once the system is validated it would be integrated into the welding control system to provide real-time feedback that would control the welding process.

Even without closed loop process control, the significant advantage of a monitored arc welding process with a digital record of the process parameters, will be the removal of the requirement for interstage non-destructive evaluation (NDE). The removal of interstage NDE will achieve significant reductions in process time – and therefore cost – as the non-added-value cooling and subsequent re-pre-heating will no longer be required. As the narrow gap gas tungsten arc welding (GTAW) process is not unique to the welding of large scale nuclear components, the benefits of the SIMPLE system will extend into other industries such as oil and gas. It is also envisaged that the individual sensor technologies investigated and developed during this project can be transferred to other manufacturing process and bring benefit to other areas of the manufacturing industry,

1.2.1 Current Phase Target Technology Area

The development of a fully integrated single manufacturing platform is beyond the scope of this development programme, as is the development of a fully automated mechanised arc welding control system. The objective of the SIMPLE demonstrator to show the synchronised data capture from a collection of digital sensing technologies to enable detection of welding imperfections.

1.3 Current state of the art

In pressure vessel manufacture one of the most time consuming operations is that of large diameter circumferential joining operations, which are performed on cylinder-to-cylinder and cylinder-to-domed closure heads. Figure 1-2 shows one such welding setup on a small scale diameter component at the Nuclear AMRC.

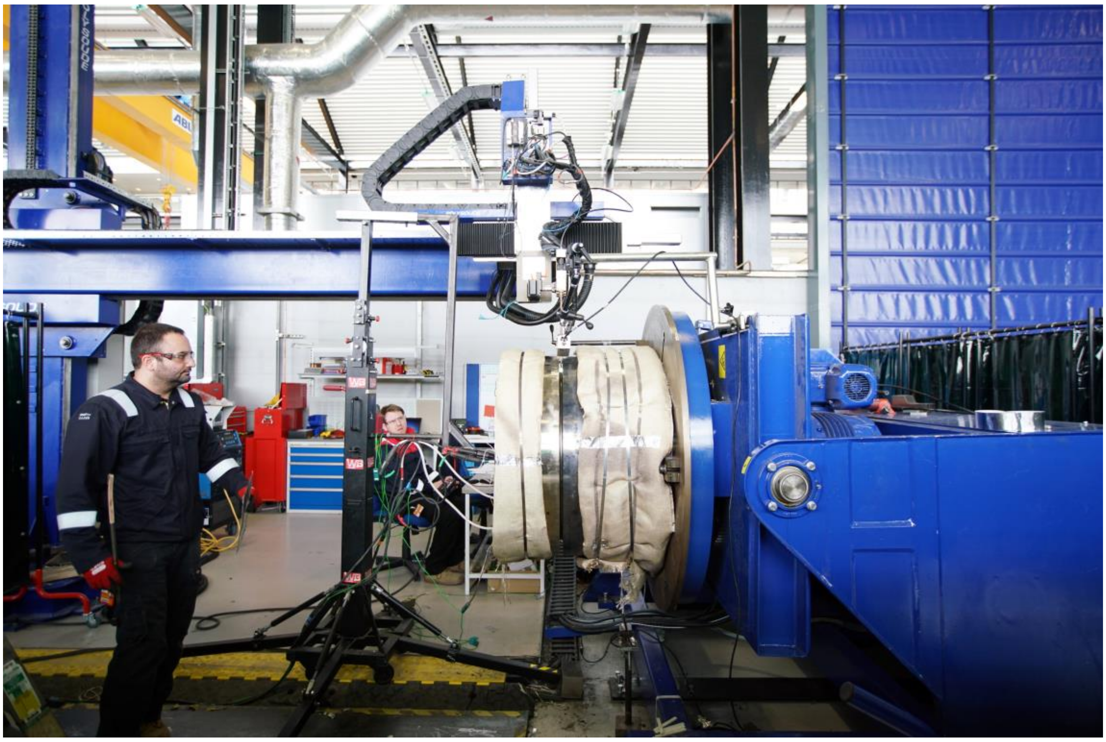

Figure 1-2: Two cylinders being welded with a column and boom rig.

In current manufacturing methods, a welding procedure specification (WPS) is developed by a fabricator during the prototyping of the component. In production, the WPS is followed by the operator with the aim of generating welds of consistent and repeatable quality, free of imperfections requiring subsequent mitigation. In addition to this, the qualified operator will use their manufacturing experience to make fine adjustments to the process based on the sound of the weld and visual inspection to attempt to mitigate spontaneous disturbances to the process that can lower weld quality.

The thickness of the finished weld is such that repair of imperfections at the bottom of the weld is impossible in the fully-welded condition. Consequently, the welding process is undertaken in stages. The process has to be stopped on a number of occasions so that interstage NDE can be undertaken and any imperfections repaired before continuing with the welding process. Additionally the welding process requires the component to be pre-heated to 175^{o}C before welding can commence whereas the NDE has to be undertaken at room temperature. Due to the size of the components the pre-heating and cooling at each stage can add many days to the manufacturing process. The most commonly used NDE process is ultrasonic testing to BS EN ISO 17640:2010 (1).

2 Overview of technical challenge for industry

To recap, the Nuclear AMRC aims to demonstrate an integrated, synchronised, in-process monitoring system for welding. This includes defect identification techniques, with the intention of moving towards automatic feedback control. This approach will create a data platform and range of analysis techniques. The requirements for the demonstration of the system is as follows:

- Demonstrate an industrially relevant application.
- Gather significant quantities of data for training datasets for the various machine learning algorithms.
- Control the process sufficiently to provide robust, repeatable data.
- Induce known flaws at specific locations in a consistent, controllable manner.

To meet these requirements, it was necessary to specify a welding application that was both representative of the large scale end application, but also of a size that was practical to run in a research environment.

2.1 Evolution from first principles

The SIMPLE demonstrator system in this phase aims to demonstrate a solution to these issues by reducing operator dependency, automating locating defects, and in the future preventing defects altogether.

GTAW was the selected application for this phase of SIMPLE. However, the approach is technology agnostic and can equally be applied to other welding processes (e.g. electron-beam, submerged arc welding, etc.).

To prepare two cylindrical components for welding, they must first be machined to produce a bevel to give the welder access to the full wall thickness. This allows for a uniform weld that guarantees the integrity of the component. Welding convention is that this bevel is at 60 degrees to the horizontal. This approach is used extensively for thin and medium section welding however as the thickness of the material increases the volume of deposited weld material becomes excessive resulting in disproportionately lengthy welding times.

As material thickness increases, the convention is to move to a 'J' profile weld preparation, where the adjustment in geometry reduces the volume of the bevel. This reduces the volume of weld material and speeds up the welding process. Consequently, a 'J-prep' was chosen for the SIMPLE demonstrator as it is a representative weld geometry used in the production of nuclear components (2).

Error! Reference source not found. shows a J-prep bevel compared to a plain bevel, where WT is the wall thickness, A is the bevel angle, T is the root face, R is the bevel radius, L is the land, and W is the half opening.

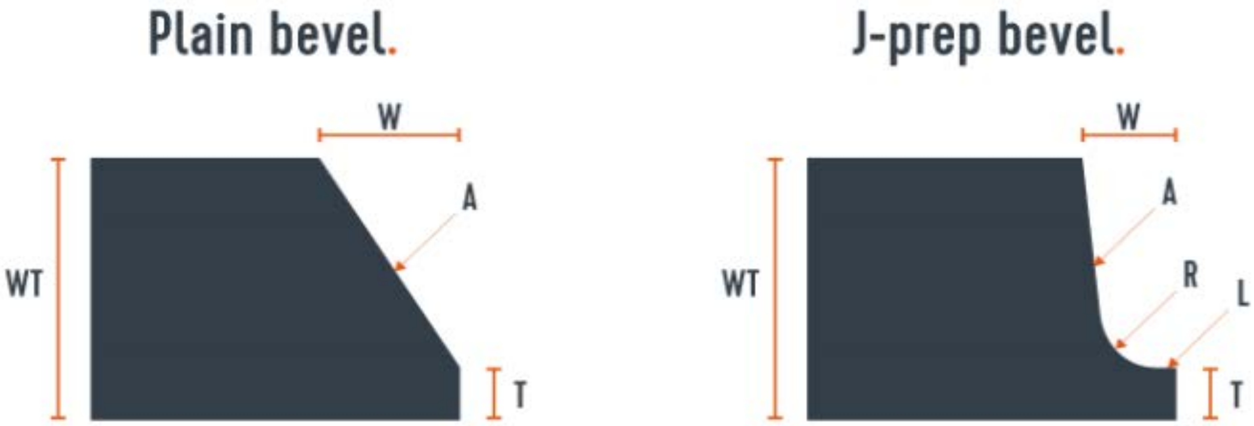

Figure 2-1: Weld preparation geometry. Ordinary bevel (left) and J-prep bevel (right). (3)

2.2 Work conducted and the development path

A full description of the system integration process is given in chapter I, however a summary of the physical integration of the sensors onto the welding equipment is outlined below.

2.2.1 Sensors

The first phase of the SIMPLE demonstrator was to establish coordinated acquisition of data from a weld pass. The data collected included a 3D laser profile of the groove, in-process voltage and amperage data, high quality video, acoustic data, and distance travelled of the weld head.

The Nuclear AMRC's Polysoude column and boom system (Figure 2-2) fitted with an NG 8-300 welding head was used for the development and demonstrator trials but the demonstrator was constructed in such a way that it could easily be transferred to another manufacturer's welding equipment.

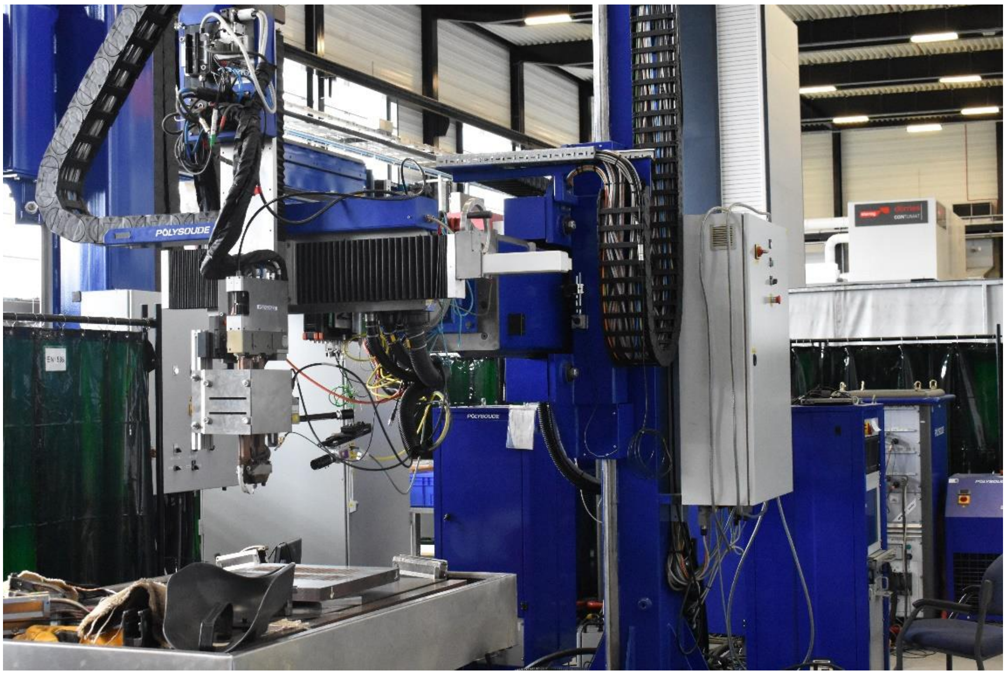

Figure 2-2: Polysoude welding system

Figure 2-3 (right) shows the placement of the sensors on the weld head. The laser scanner was positioned 140 mm behind the weld head to capture the 3D profile of the cooling weld beads. This data can be coordinated with the distance travelled to synchronise the profile at any point with the acoustic, power, visual data and laser data.

An acoustic sensor was placed on the weld head to capture all sound from the process. To minimise the effect of random uncontrollable noises in the environment, a second microphone was placed several metres away on the Polysoude boom. This allowed background noise recorded by both microphones to be removed from the data to produce a more representative audio file generated by the weld process.

Finally, the weld head supported a high definition camera focussed on the weld pool and trailing bead geometry. This data was used to train a model capable of predicting whether the weld would produce a defect and identify what type of defect it would cause. In welding vision systems it is typical to also capture images from ahead of the welding pool, however in this application the wirefeed system obscured this view.

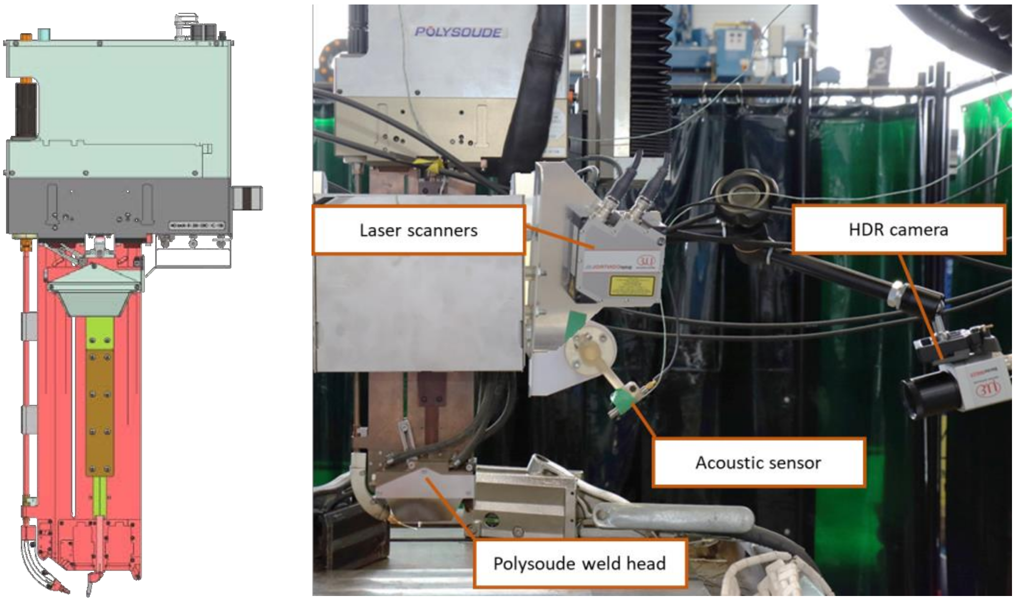

Figure 2-3: Polysoude NG-8-300 weld head (left), sensor location on the weld head (right)

During the development of the system, a webcam was placed some distance from the welding process to record the activity in the welding area as it aided in identifying any external causes of anomalous data during development e.g. a spanner falling from the welding table causing an abnormal spike in the acoustic data.

Finally, the three-phase input current and voltage were measured across the three-phase supply via the power monitoring system developed by the University of Sheffield Physics and Astronomy department, with the data captured and displayed by the Dewesoft DAQ. Live power analysis was carried out and displayed with the other live data streams.

2.2.2 Sensor integration

During the development of the demonstrator system, it was necessary to design a custom sensor rig to test and evaluate the sensor locations. The major challenge was that the sensors needed to travel in alignment relative to the tip of the welding tungsten/arc which effectively required them to be attached to the head. This was made more challenging by the Polysoude system only being able to accommodate an additional weight of 10kg on the head and so the weight of all the sensors, bracketry and cabling had to be below this limit. To achieve this, bracketry was designed to attach to existing mounting points of the welding head, with the specific requirement for it to not interfere with the welding process. CAD files (Figure 2-3 left) of the welding equipment provided by Polysoude aided the design of the bracketry.

2.2.3 Data Synchronisation

Synchronisation of the data with the position of the workpiece is critical to valid analysis and identifying the location of an imperfection within a workpiece. The Dewesoft system uses EtherCAT synchronisation to acquire the DAQ data streams (acoustic, power monitoring and encoder position sensors) within 50ns. This data is also correlated to positional data captured from an encoder attached to the boom to this accuracy, allowing the physical location of the head to be captured in reference to any imperfections. The vision and laser sensor data are synchronised when the data is stored at the cabinet but there is a minor delay from when the data is captured to it received from the PC. Given the refresh rate of the camera and laser profile sensors and the transport medium, the data streams will be synchronised within approximately 25ms. This synchronization could be improved by using dedicated synchronisation hardware connected to the EtherCAT devices. This delay could be compensated for by use of a hardware trigger, or avoided by use of sensors with EtherCAT interfaces in future systems. More can be read about the data synchronisation in the integration report (chapter I).

2.2.4 Welding trials

To test and demonstrate the full data acquisition system, the welding trials were specified to be representative of large diameter pressure vessel. Flat plates of SA508 grade 3 class II pressure vessel steel were used to act as representative sections of a large diameter circumferential weld as at large diameters the 3D weld geometry is almost identical with that of a flat plate.

The scope of this project was primarily a data-gathering exercise where acceptable welds would be created to provide baseline data, as well as welds with known flaws to prove the concept of the system (where the controllable weld process parameters were intentionally set to produce defects). To help bound the problem and limit the number of experimental variables to a practicable level, the effects of fit up and distortion during the process were deemed beyond the scope of the research at this stage. As such, the welds were undertaken in representative grooves that had been machined into single test pieces to simulate a perfectly mated butt joint.

Square test coupons of 225 mm a side were prepared with J-groove designs as per ISO 9692-1 (Figure 2-4). Groove depths ranged from 25 mm to 50 mm to maximise the use of available material, with the assumption being that a 50 mm groove would be sufficiently representative of a 100 mm section weld.

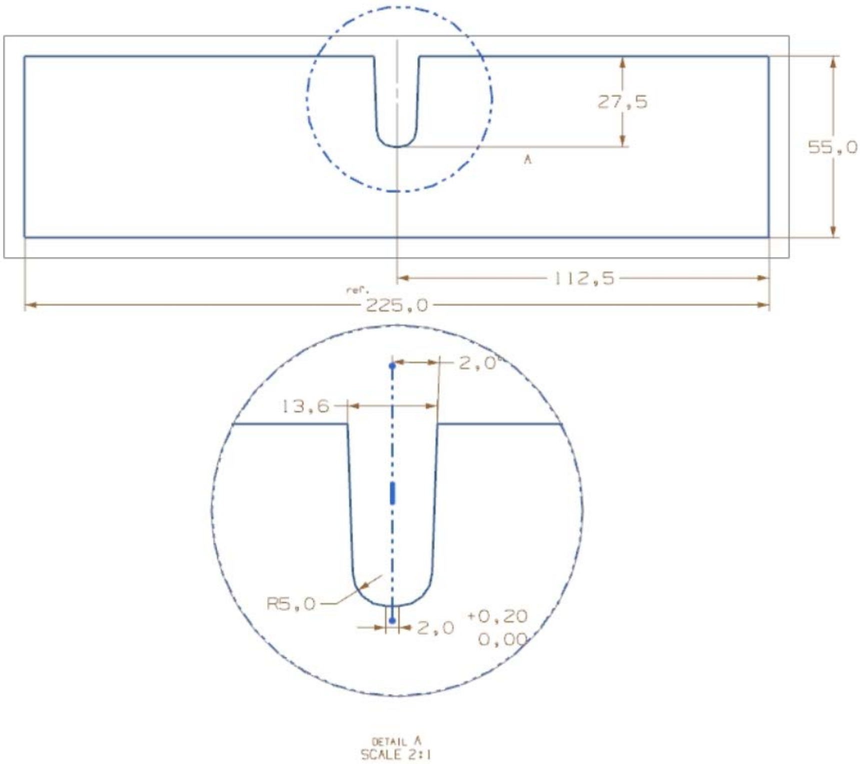

Figure 2-4: J-prep groove geometry

To draw meaningful conclusions from the captured data, both acceptable welds and welds with induced imperfections had to be performed to develop and validate the system.

An acceptable weld is characterised by the British Standard BS-EN-11666. To ensure the baseline welds complied with these standards, a WPS was developed based on prior Nuclear AMRC experience. The parameters used in the WPS for the baseline welds are shown in Table 2-1.

Table 2-1: Baseline welding parameters

Parameter	Value
Slope time	4.0 s
Current	335.0 A
High pulse time	250 ms
Base current	111.0 A
Base pulse time	250 ms

NDE was undertaken to confirm the baseline parameters. Ultrasonic inspection was carried out in line with BS-EN-17635 (4) with the acceptance criteria meeting BS-EN-11666 (Acceptance level 3) (5). The inspection showed all samples to be satisfactory from the root to 22 mm from the top surface. The area in which the baseline welds were deposited

To induce known imperfections into the welds, the operator deviated from the WPS to give the weld sub-optimal characteristics.

In this experiment, nine substandard welding variables that may cause conditions that can lead to imperfections were used, and each condition set was repeated eight times. The variables and their results are shown in Table 2-2.

In between the eight runs of each variable, two baseline welds were deposited to leave a clear boundary between each flawed run. 12 additional baseline runs were also deposited into the final plate to give additional validation data.

Table 2-2: Welding variables and their effects

Variable	Effect
Poor quality tungsten	Wire not melted correctly – arc wanders
Low wire feed speed – 500 mm/min	Potential metallographic differences
High wire feed speed – 2000 mm/min	Too much deposition
Tungsten offset close to sidewall / 2 mm	Excessive fusion (undercut)
Tungsten offset very close to sidewall / 1 mm	Sidewall arcing – bead irregular
Shielding gas low	Porosity/oxidation
Shielding gas too high	Porosity
Tungsten position down centre of groove	Lack of sidewall fusion
Wire feed directed away from arc	Wire not melted correctly

2.2.5 Data capture

Excluding the data from the visual capture system and the laser scanners, all the data was recorded directly by the Dewesoft DAQ and stored locally. The data from the laser scanners and vision system were time-stamped with the encoder data from the Polysoude, allowing the data to be correlated to the physical location on the test coupon. Figure 2-5 shows a screenshot of the Dewesoft software recording of a weld. The software allows the data display to be easily customised during and after the weld.

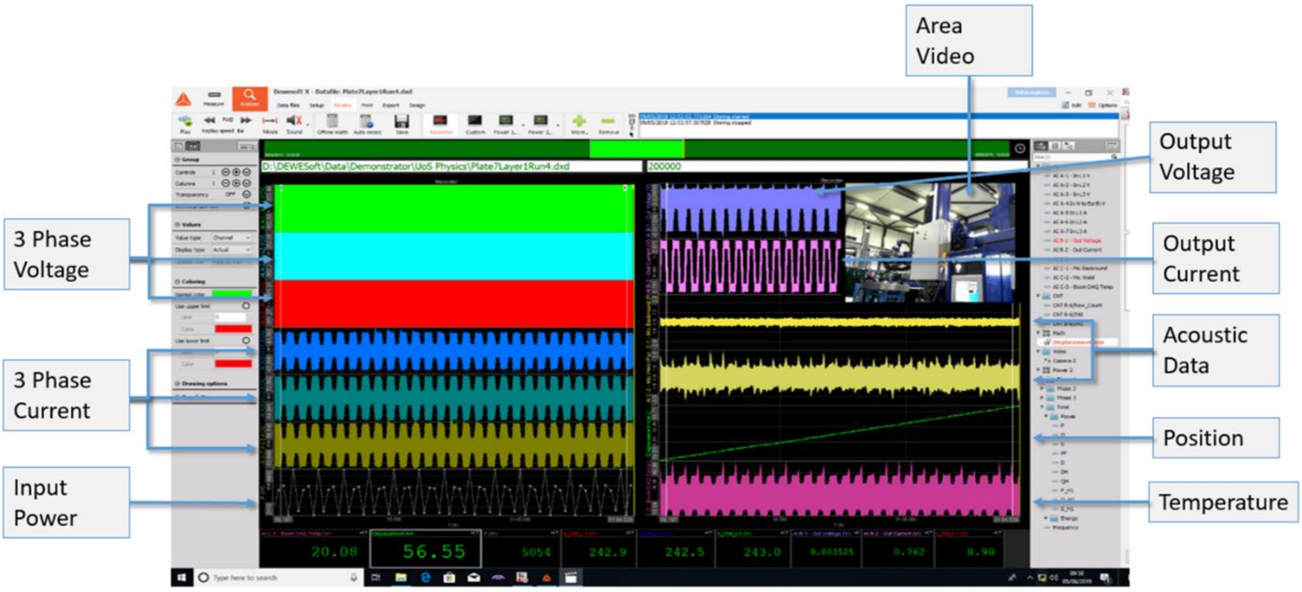

Figure 2-5: Screenshot of Dewesoft software during a recording of a weld.

If a disturbance in a signal is noticed and indicates a possible imperfection then the distance travelled by the head at that point is known so that the plate can be cut at that location allowing micrograph and macrograph images to be created.

2.2.6 Workpiece analysis

Each plate was initially cut at three locations along the weld. A macrograph was taken for the full groove at 34x magnification, along with 70x or 170x magnification photos for each defect. Examples are shown in Figure 2-6.

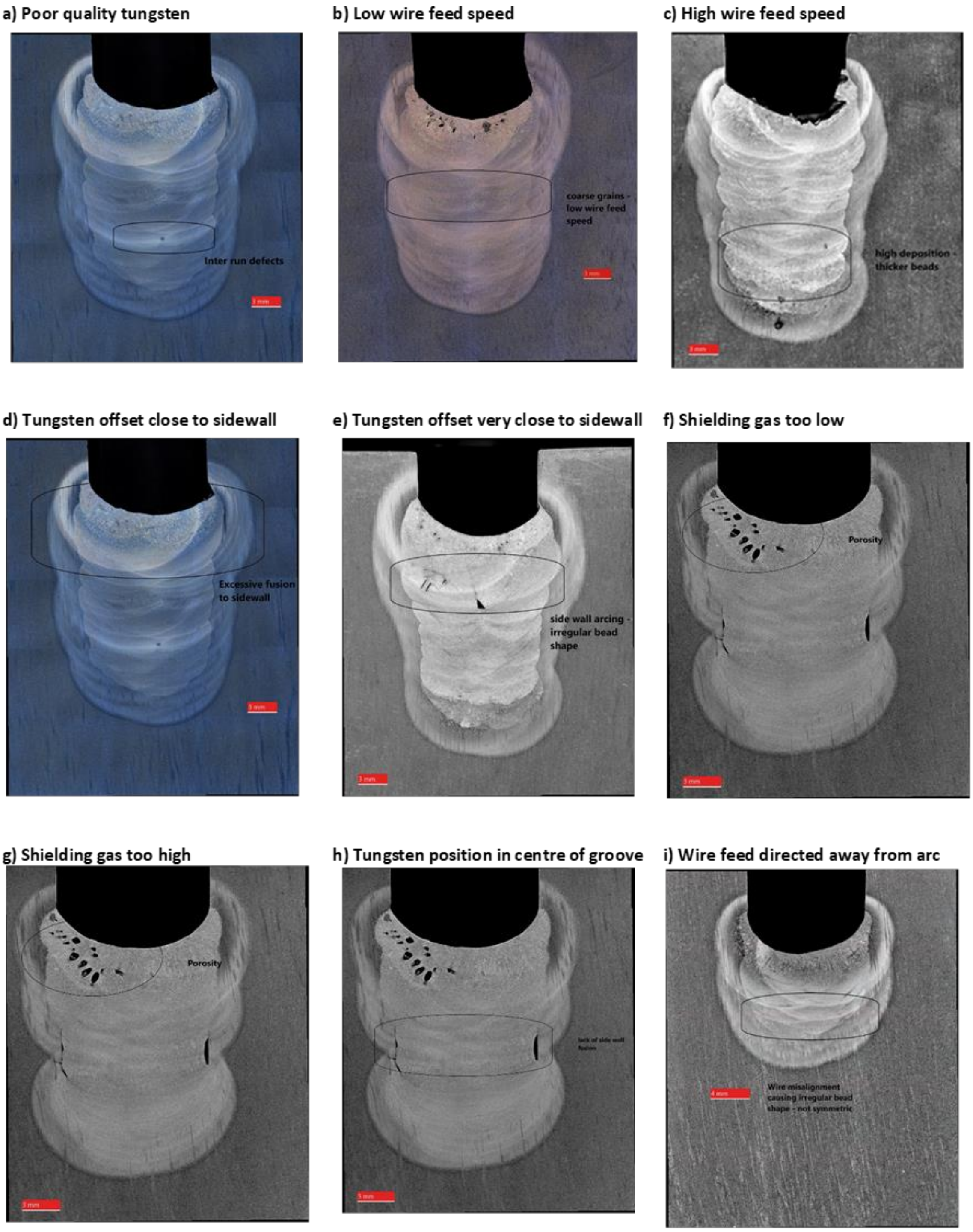

Figure 2-6: Demonstrator weld macrographs

2.2.7 University of Strathclyde Demonstrator

In parallel to the SIMPLE demonstrator housed at the Nuclear AMRC, the University of Strathclyde produced their own system to demonstrate the feasibility of using ultrasonic inspection in the proposed environment (Figure 2-7).

The system was set up to address challenges associated with in-process inspection such as hydrogen cracking, beam bending due to temperature gradients, false positives, and the tolerance of the sensor due to elevated temperature.

Experiments to address these issues have been outlined, and where possible, tested in the robotic welding cell at the University of Strathclyde. More information on the scope of the work package and the results can be found in chapter D.

Figure 2-7: AFRC demonstrator system

3 Recommendation for further research and development

3.1 Future work

The short term development path for the SIMPLE demonstrator system has two main requirements; continued discrete development of the sensor systems, and the creation of a multivariate analysis system that exploits the synchronised captured data.

At the current stage of development, the SIMPLE demonstrator has four discrete sensor systems integrated into one common platform. Each of these sensors has analysis software capable of providing near to real time information to the operator. It has been shown that this information can be correlated to conditions that lead to welding imperfections, however, the confidence of this correlation is not consistent across all sensors. Significant work is still required to develop the analysis methods to meet the requirements of full autonomy.

To progress towards a more autonomous system the following developments should be made:

3.1.1 System development

- Further development of the sensor analysis systems to increase confidence intervals to consistent and acceptable limits.
- Application of the sensors to other materials and welding geometries commonly found in the nuclear manufacturing industry.
- Integration of the ultrasonic sensor system.
- Development of a user friendly GUI for the data capture system capable of indicating key information directly to the operator. For example;
    - KPIs from the laser scanners (gap width, deflection angle between mated surfaces etc.).
    - A traffic light system from the sensor data (e.g. **acceptable weld**, **weld at risk**, **imperfection detected**).

3.1.2 Process and application development

- Application of the demonstrator system to representative scale cylindrical components.
- Development of analysis methods to data mine the synchronised data source.
- Outputs of the individual and combined sensor data to be analysed to find correlations to welding imperfections.
- Provision of validation welding sensor data captured from production environments.

- Interventions made by the operator should also be captured to study the effect of mitigation actions on the welding process.

- Feasibility studies into closed loop control.
- Review of the system and identification of other industrial manufacturing process that can benefit from these developments.

3.2 Route to industrial adoption

The cost, lead-time and integrity requirements of nuclear components mean that the nuclear manufacturing industry is understandably risk averse and conservative when it comes to deploying new manufacturing methodologies. Consequently any proposed autonomous system would have to be proven to high levels of repeatability and redundancy. The cost of producing a fully autonomous system at this stage is not justifiable. A more practicable route would be a phased roll out of the technology.

Initially, the process would have full operator control with the output of the analysis system displayed to the operator, requiring them to make a correction to the process or to manually halt the process if a defect is identified. During this phase any inputs made by the operator and adjustments to the welding process would be captured by the next SIMPLE demonstrator system. To best make use of this data, end users of the system would be required to share this data with the SIMPLE developer to enable a sizeable body of knowledge to be built with the continuing benefit of rapid sharing of the improvements in the weld control system. To properly close the loop there would be a need for the end users to update the system with details of subsequent imperfections found during NDE.

The second phase would use the improvements to the weld control system from the data captured in phase 1 to detect unfavourable welding conditions in near real time and make suggestions to the operator to correct the process. These suggestions would be based on metrics directly from the sensors (e.g. distance from the sidewall) as well as historic data from similar welding events captured across the supply chain. The operator would still have full control of the system at this stage, though the success rate of the interventions suggested by the system would be captured for analysis.

Phase 3 would then be analogous to an autopilot. The semi-autonomous system would keep the welding conditions within an 'optimal' range, making minor adjustments set within a specified confidence range. If disturbances occur that are outside of this acceptable range, a skilled operator is required to intervene to correct the process. As the system is developed and the frequency of operator interventions is minimalised, the evidence is gathered to support a fully autonomous welding system.

References

1. *BS EN ISO 17640:2010 Non-destructive testing of welds -- Ultrasonic testing -- Techniques, testing levels, and assessment.* s.l. : International Standards Organisation, 2010.

2. The Welding Institue. Design Part 3. *TWI Global.* [Online] The Welding Institute, 2019. [Cited: 10 June 2019.] https://www.twi-global.com/technical-knowledge/job-knowledge/design-part-3-092.

3. Felce, Alex. The importance of bevel geometry. *Subsea UK website.* [Online] Subsea UK, 10 June 2016. [Cited: 10 June 2019.] https://www.subseauk.com/documents/presentations/alex%20felce%20(oms)%20-%20the%20importance%20of%20bevel%20geometry.pdf.

4. *BS EN ISO 17635:2016 Non-destructive testing of welds. General rules for metallic materials .* s.l. : BSI, 2016.

5. *BS-EN-11666 Non-destructive testing of welds. Ultrasonic testing. Acceptance levels .* s.l. : BSI, 2018.

K. Dissemination

Single Manufacturing Platform Environment (SIMPLE) - Stage 2

Dissemination

NI1032-REP-07

NUCLEAR AMRC
ADVANCED MANUFACTURING RESEARCH CENTRE

Project report

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Contents

1 Dissemination

Stage two of the Simple project ran for 19 months between February 2018 and August 2019. Over the duration of the project, there have been extensive direct and indirect dissemination activities carried out by the Nuclear AMRC and the project consortium.

1.1 Consortium networking

Seven consortium meetings were held during the project, with each consortium partner hosting at least one meeting. At these meetings, the progress of each work package was shared between the delivery teams as well as to the funders, the Department for Business, Energy and Industrial Strategy (BEIS) and their technical advisors the Nuclear Innovation and Research Office (NIRO). These meetings had a primary function to ensure the consistent successful delivery of the programme, and enabled each of the delivery partners to share their wider capability.

Table 1-1: Consortium meetings

Consortium Meeting	Date	Host
Kickoff Meeting	2nd Feb 2018	Nuclear ARMC
Quarterly review meeting 1	2nd May 2018	Nuclear AMRC
Quarterly review meeting 2	17th July 2018	Peak NDT
Quarterly review meeting 3	24th October 2018	TWI Ltd (Cambridge)
Quarterly review meeting 4	12th February 2019	University of Strathclyde
Quarterly review meeting 5	16th May 2019	Nuclear AMRC
Project close out meeting (in conjunction with the InFORM project team	23rd July 2019	Nuclear AMRC

1.2 Conferences, seminars and other events

The output of the research conducted has been presented and discussed at a number of industrial and academic conferences and seminars domestically and internationally. A summary of the presentations is given in Table 1-2, full abstracts can be found in Appendix 4

Table 1-2: Conferences and seminars attended for the Simple project

Conference	Date	Research area, Organisation
ASME Pressure Vessels and Piping (PVP) 2018 Prague, Czech Republic	2nd February 2018	Overall project, Nuclear AMRC
National Structural Integrity Research Conference (NSIRC) 2018 Cambridge, UK	3rd July 2018	Visual sensor, TWI Ltd.
BEIS Nuclear Innovation Programme suppliers day event, Birmingham UK	14th January 2019	Overall project, Nuclear AMRC
Lamdamap 13 Rotherham	13th March 2019	Laser sensors, Nuclear AMRC
ASME International Conference On Nuclear Engineering (ICONE) 27 Tsukuba, Japan	19th May 2019	Overall project, Nuclear AMRC
International Congress on Welding, Additive Manufacturing and associated non-destructive testing (ICWAM) 2019 Metz France	5th June 2019	Ultrasonic sensors, University of Strathclyde
Nuclear Innovations Conference, Sheffield, UK	2-3rd July 2019	Overall project, Nuclear AMRC
72nd International Institute of Welding annual assembly Bratislava, Slovakia	7th July 2019	Acoustic sensors, Nuclear AMRC
72nd IIW annual assembly Bratislava, Slovakia	7th July 2019	In-process monitoring, University of Sheffield Physics and Astronomy
American Welding Society Annual Conference 2019	11th November 2019	In-process monitoring, University of Sheffield Physics and Astronomy

1.3 Dissemination events

The Nuclear AMRC has organised two events with the focus of dissemination of the output of the Nuclear Innovation Programme (NIP). The first was an academically focussed event utilising the NNUMAN (New Nuclear MANufacturing) community. The second event was the Nuclear Innovations UK conference, an industry focussed event co-hosted with NNL but funded entirely from the Nuclear AMRC NIP projects (SIMPLE and INFORM) in addition to conference fees charged to attendees.

1.3.1 NNUMAN dissemination event

NNUMAN was an £8 million Engineering and Physical Sciences Research Council (EPSRC) research programme that ran from 2012-2017 covering a wide range of nuclear-relevant manufacturing research including joining technologies, powder metallurgy, and advanced machining and surface engineering. Through the dissemination activities of the programme, a community of over 80 interested parties was formed. After the funding period ended it was decided to continue to build upon this network and formally meet to discuss relevant research activities every 6 months. NNUMAN is chaired by the Dalton Institute of the University of Manchester with strong involvement from the Nuclear AMRC.

In addition to the standard biannual meetings, the Nuclear AMRC held a specific dissemination seminar for the advanced manufacturing and materials (AM&M) strand of the NIP to the NNUMAN community at the AMRC's Knowledge Transfer Centre, Rotherham on the 16th January 2019. It was attended by over 75 members of the nuclear R&D community across industry and academia and 7 projects from the five AM&M themes (including SIMPLE from theme 2) were presented at the event.

1.3.2 Nuclear Innovations Conference (NIC)

The first Nuclear Innovations UK Conference was held at Cutlers' Hall in Sheffield (Figure 1-1) and Nuclear AMRC on the 2nd and 3rd of July 2019. The event was organised by the Nuclear AMRC and NNL to present the outputs of the entire NIP to the UK nuclear community and beyond. The event was attended by over 275 guests representing companies from every aspect of the nuclear sector – vendors, the wider nuclear supply chain as well as related industries – with feedback showing it was very well received by the attendees.

A technical presentation of the work conducted in SIMPLE was presented on each day at Cutlers' Hall as were coach tours to Nuclear AMRC, Rotherham to view live demonstrations of the integrated system capturing data during welding (Figure 1-2).

Figure 1-1: Nuclear Innovations UK Conference, 2-3rd July 2019, Sheffield

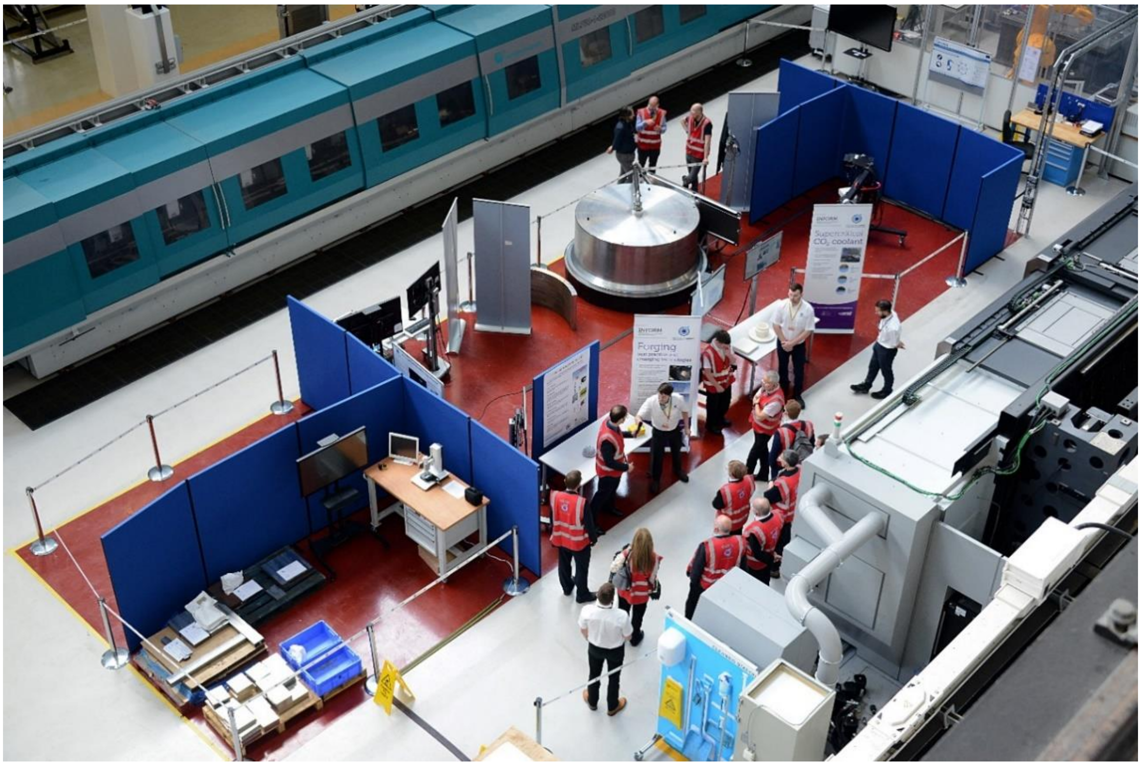

Figure 1-2: NIUK conference tours of Nuclear AMRC

1.4 Industrial engagement

The Nuclear AMRC has far reaching connections into the nuclear supply chain, and this was exploited during the project to both disseminate the research, but also receive direction to ensure that the developed system will have relevance to the nuclear sector.

1.4.1 Nuclear AMRC Research Board

One of the ways that the Nuclear AMRC ensures it remains industrially relevant is by way of its membership. There are two grades of membership, Tier 1 members contribute £200K p.a. in cash or kind and have one seat on the Research Board. Tier 2 members contribute £30K p.a. in cash or kind and all Tier 2 members nominate one person to sit on the Research Board to represent their interests. The Research Board represents over 40 companies from across the nuclear supply chain – including reactor vendors – and meets quarterly. The Research Board reviews the research that Nuclear AMRC are undertaking on their behalf and also receive presentations about other publicly funded research we are undertaking. Consequently progress updates on the SIMPLE project were given at each quarter's meeting throughout the life of the project.

1.4.2 BEIS Suppliers Day Event

The BEIS Nuclear Innovation Programme Suppliers Day Event held in Birmingham on the 14th January 2019 aimed to disseminate findings from the initial phases of the £180m BEIS investment through the Nuclear Innovation Programme (NIP) and promote opportunities for the next phases of work. At the event, Phase 1 participants for the Advanced Reactor Design – Digital and Advanced Manufacturing and Materials programmes – disseminated findings from their work through presentations and Q&A sessions. This enabled knowledge to be shared with the wider industry, helping to promote fairness and transparency for potential suppliers and collaborators that wish to bid into future phases of work. Participating stakeholders were invited to engage in a brokering and networking event to stimulate discussions about potential collaborations for the next phases of work (2). Additionally the details of the next phase of the Advanced Manufacture and Materials funding call were given. This was to provide up to £20 million of government funding to demonstrate how advanced manufacturing and construction can increase UK competitiveness.

1.4.3 Supply chain engagement

The Nuclear AMRC is a hub for the nuclear manufacturing sector. It is used to showcase technologies and facilitate the dissemination of information. As such, the Nuclear AMRC is constantly meeting and engaging with governments, industry, academia and the wider public. For example at the time of print (August 2019), in the past 10 months the Nuclear AMRC, Rotherham has hosted 137 small and medium enterprises (SMEs), 96 large companies, 33 academic organisations and 40 other government organisations. Many of these organisations will have been taken on tours of the Nuclear AMRC shop floor which will have involved passing work stations where individual sensors were being developed as well as the SIMPLE demonstrator when it was being built and tested. It is common practice when taking visitors past the various work areas to explain any projects which we are at liberty to do so (i.e. not commercially-funded projects). Consequently, the SIMPLE project has been widely disseminated to a significant majority of the 300+ organisations that have been at Nuclear AMRC, Rotherham over the last 10 months.

1.5 Further dissemination

Though the funding period will come to an end in August 2019 the various outputs of the SIMPLE project will continue to be disseminated by the project consortium. Numerous academic journal publications are planned and are detailed in Appendix 4. The system demonstrator will continue to be on exhibition on the shop floor at Nuclear AMRC, Rotherham, and will therefore continue to be showcased to the extensive numbers of visitors at the Nuclear AMRC.

In addition, work is ongoing to build industrial engagement for subsequent funding programs. This will be essential to continue the development of single manufacturing platform technologies to a maturity where they can be adopted and exploited by industry.

1.5.1 MANTRA

MANTRA, the MANufacturing (technology) TRAnsporter, is a specially customised 14 meter HGV trailer which is operated by the University of Sheffield AMRC. It is packed with the latest machinery and simulators designed to give aspiring young engineers a hands-on experience with real cutting-edge technologies (1). The MANTRA lorry regularly tours schools and colleges to give students a taste of modern manufacturing, advanced modelling and assembly line technology to help inspire young people to take up careers in engineering. It also attends industrial events where it showcases the latest developments in advanced manufacturing technology to the wider business community and commercial audiences.

Videos highlighting the results of the SIMPLE project have been installed into MANTRA and will be displayed at future exhibitions and in schools and colleges to demonstrate the impact the innovations will have on improving UK manufacturing competitiveness.

References

1. **AMRC.** Welcome to AMRC Mantra. [Online] 2019. [Cited: 14 08 2019.] https://amrcmantra.co.uk/.

