The University Of Sheffield.

NUCLEAR AMRC
ADVANCED MANUFACTURING RESEARCH CENTRE

# SIMPLE

## Single Manufacturing Platform Environment

**First phase R&D (2018–19)**
supported by the Nuclear Innovation Programme

namrc.co.uk

Department for Business, Energy & Industrial Strategy

CATAPULT High Value Manufacturing

European Union European Regional Development Fund

# The Simple project aims to integrate a range of fabrication, machining and inspection operations onto a single manufacturing platform.

**Single-platform manufacturing reduces the need to move large components between work areas, and helps ensure accuracy and quality control throughout the manufacturing process.**

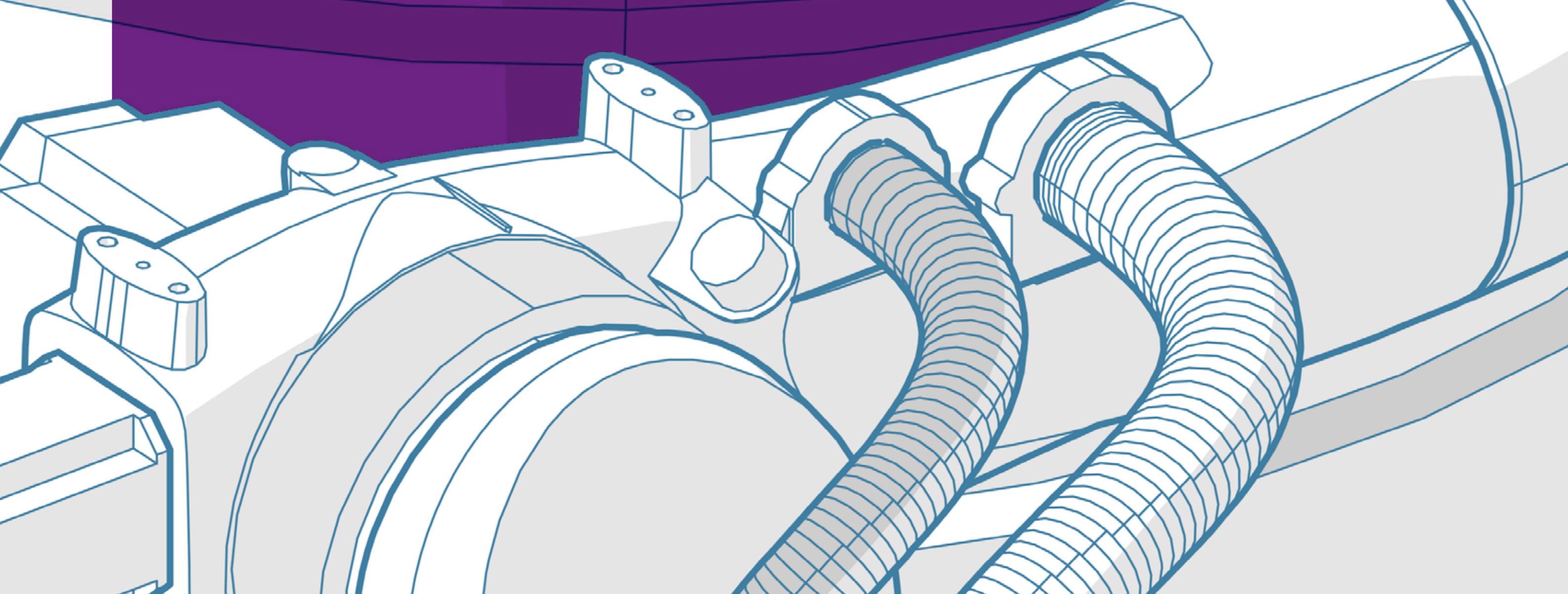
As a first step, the Nuclear AMRC led a 20-month collaborative research programme to develop the digital manufacturing techniques that will underpin a host of single-platform tools.

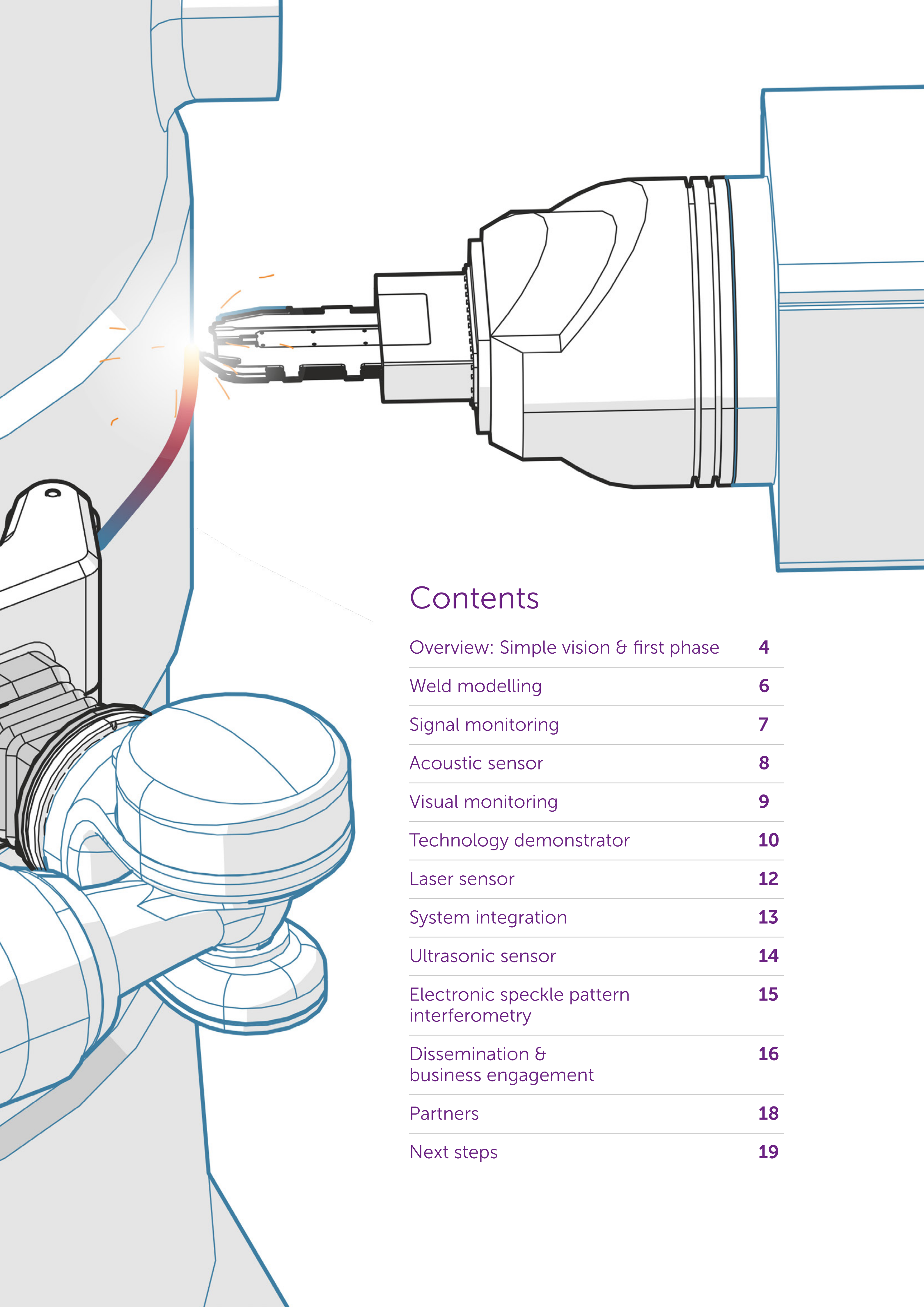
To prove the Simple concept, we demonstrated these digital techniques by developing an integrated welding and monitoring tool. Combining a range of sensors and analytical tools with a mechanised arc welding head, this tool can allow automated in-process inspection of welds, improving quality and production efficiency.

This report summarises the research to date, and sets out directions for continuing development.

The first phase of Simple was supported by £1.35 million funding from the Department for Business, Energy & Industry Strategy (BEIS) as part of the Nuclear Innovation Programme.

Research partners included the University of Sheffield's Enabling Sciences for Intelligent Manufacturing team and Advanced Manufacturing Research Centre, the University of Strathclyde, TWI and Peak NDT.





# Contents

# The Simple vision

**The Simple project aims to significantly improve productivity for large nuclear components, by carrying out the full set of manufacturing operations on a single platform, and automating common tasks such as weld inspection.**

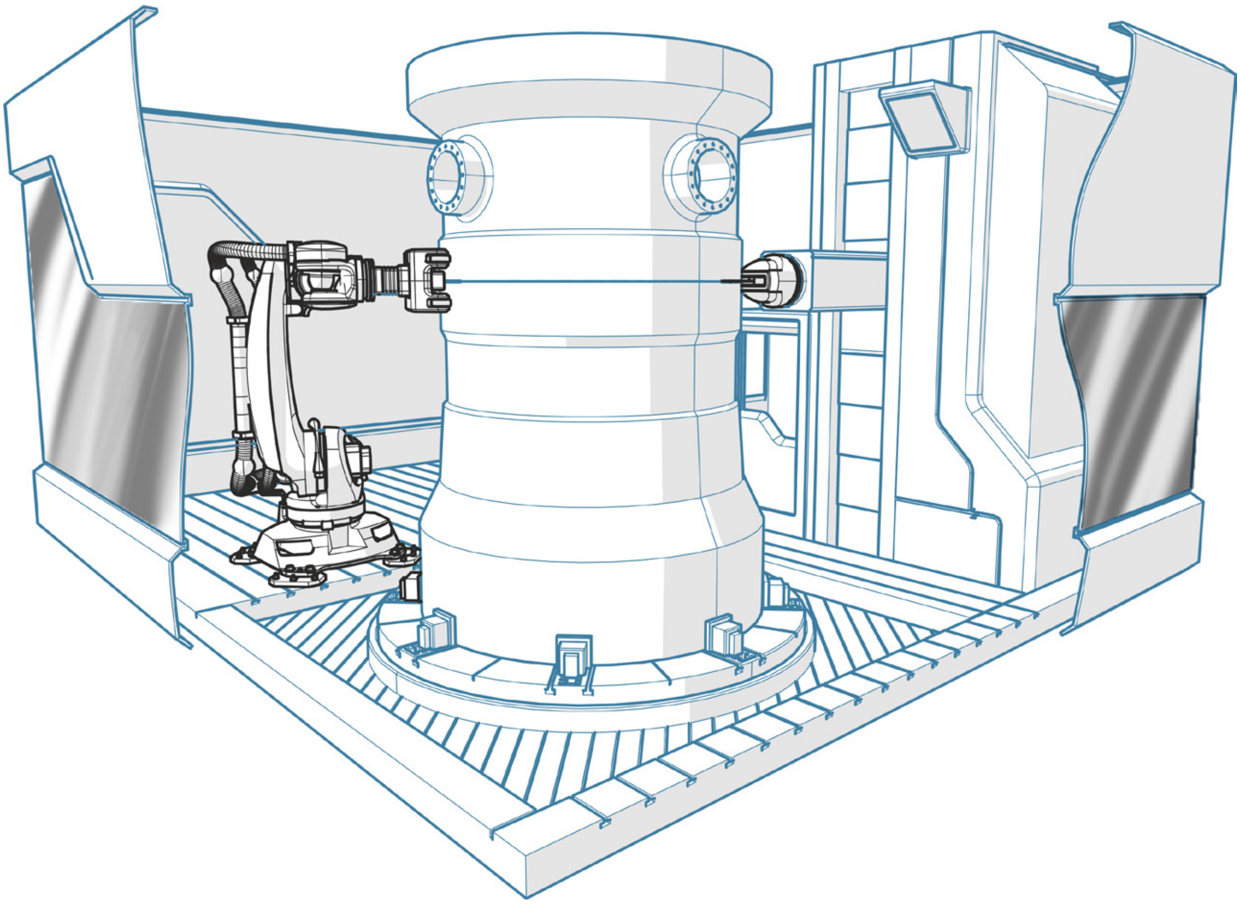
Our vision of single-platform manufacturing is focused on reducing the production cost of large complex components measuring at least two metres, including pressure vessel sections, large valve casings and decommissioning waste containers.

The Simple approach could also be used to reduce the risk of manufacturing error and cut cost and time for smaller high-value components for the nuclear sector, and be deployed in other sectors such as energy, oil & gas, marine and aerospace.

Single-platform manufacturing will depend on a comprehensive selection of innovative machining, welding, cladding and inspection tools which can be deployed on a single integrated manufacturing cell, as well as digital techniques to analyse and act on large amounts of real-time data. The Simple project aligns with the so-called fourth industrial revolution (4IR, or Industry 4.0) by combining digital and physical systems to improve productivity and allow autonomous decision-making.

Our initial studies have shown that the Simple approach to single-platform manufacturing could achieve cost and time savings of at least 50 per cent for a range of large complex fabrications.

Simple is supported by a range of nuclear industry partners – including reactor developers and operators, as well as decommissioning site owners – who ensure the research is addressing industry challenges. The results are being shared with UK industry, including the Fit For Nuclear network of companies from along the supply chain.



# First phase

**The first phase of research successfully demonstrated an innovative integrated welding and monitoring tool which exploits Industry 4.0 techniques for data management, proving the concept of the Simple vision.**

We chose this tool as a technology demonstrator because welding is an extremely data-rich process, including visual and audio data. If digital manufacturing techniques can successfully collect and analyse synchronised data from welding, then other processes or sensor combinations will present fewer challenges.

In-process monitoring of welding can also significantly improve productivity, by mitigating the need for repeated non-destructive evaluation between weld passes. This will reduce the time required for a complete thick-section weld while maintaining quality and recording a detailed history of the weld process.

The 20-month first phase of the Simple programme started in January 2018, and completed on schedule in August 2019.

Following initial work including process selection, systems engineering and sensor development, we started trials of individual sensors in June 2018, using a Polysoude narrow-groove welding torch at the Nuclear AMRC in Rotherham. We started with single bead welds, moving on to full-depth welds by the end of the year.

Trials continued through the first half of 2019, combining a range of sensors through an innovative data integration platform, and gathering a wealth of data for process optimisation and defect identification.

Nuclear AMRC researchers developed a variety of analytical and modelling techniques which could enable full automation of the welding and inspection tool. These include a laser scanner for measuring weld geometry, and tools for acoustic analysis of the welding process, as well as early research into electronic speckle pattern interferometry techniques to characterise residual stress. Our team also developed new tools to predict weld bead geometries using an artificial neural network and machine learning.

Other project partners worked on additional inspection and monitoring technologies.

Physicists from the University of Sheffield's Enabling Sciences for Intelligent Manufacturing team developed a process monitoring system which has been integrated with the Polysoude to record and analyse the welding parameters.

TWI developed a visual inspection system, recording a series of videos of different welding conditions to train and test a neural network for real-time monitoring.

The University of Strathclyde and Peak NDT collaborated on a hot ultrasonic inspection system, with a prototype system installed on a welding rig at Strathclyde.

And the University of Sheffield AMRC developed the system to integrate data from all the sensors in real time.

The following pages discuss this work in more detail, and identify potential routes for continuing research and development.

Welding is an extremely data-rich process, including visual and audio data

# Weld modelling

Lead partner: **Nuclear AMRC**

**For effective weld process planning, you need to be able to predict the geometry of the weld beads from the input welding parameters.**

As part of the Simple project, we trained an artificial neural network to predict weld bead geometries using machine learning techniques.

Machine learning systems are increasingly used in a variety of industrial applications to discover patterns in large quantities of data from multiple sources, and make predictions based on new data.

We trained an artificial neural network – a mathematical model inspired by the biology of the neuron – on data captured during welding trials carried out at the Nuclear AMRC.

Using a Polysoude gas tungsten arc welding cell, our welding team produced a series of 56 weld specimens using a range of known welding parameters: voltage, travel speed, wire feed speed, peak current, and background current.

This initial stage of research focused on relatively simple bead-on-plate welds produced by a single pass. Currently, there are no systems capable of accurately predicting the geometry of multiple bead welding processes, due to the complex effects of successive welds on the geometry of earlier layers.

For each weld sample, we manually measured seven geometric features of the weld bead and heat affected zone (HAZ): bead height, width and cross-section area; HAZ depth, width and area; and average bead angle.

This data was then fed to a multilayer perceptron artificial neural network, using the SciKit-Learn/MLPRegressor machine learning package. Around a fifth of the data sets were not used for training, but instead used to test the accuracy of the machine learning system.

The neural network was able to predict weld geometries from these additional sets of welding parameters with reasonable accuracy. Accuracy can be improved by further training on additional data, and fine tuning of the system's parameters.

With further development, this approach could be used to automatically vary the weld parameters to produce the desired weld geometry, allowing weld processes to be planned and carried out with minimal human intervention. Extensive work is required before such systems can model the behaviour of multi-pass welds.

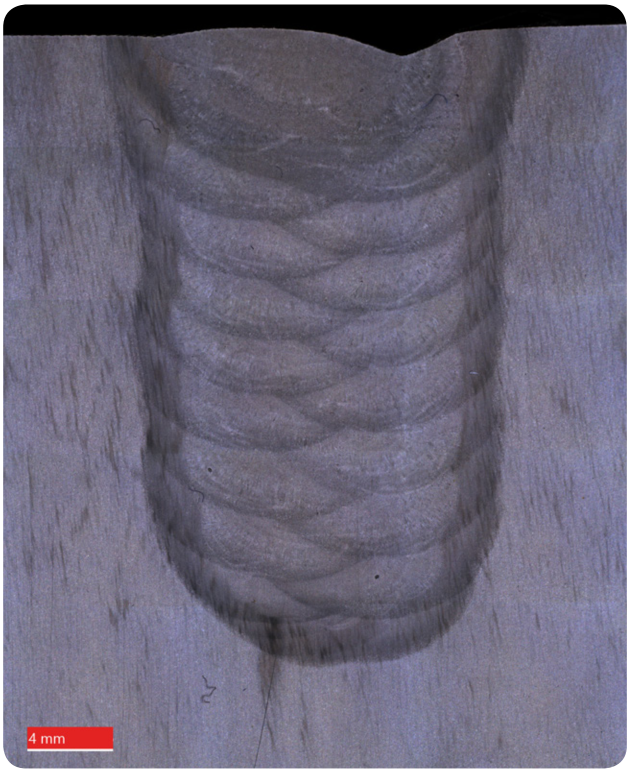
# Signal monitoring

Lead partner: **University of Sheffield ESIM**

**In-process signal monitoring of welding processes can promptly reveal the presence of any faults, and collect parameter data for use in process optimisation.**

The Enabling Sciences for Intelligent Manufacturing (ESIM) group of the University of Sheffield's Department of Physics and Astronomy successfully developed a system to measure welding voltage and current signals during the welding process.

As well as identifying welding faults from variations in the arc voltage, the signal monitoring system constantly records the electrical parameters to support process optimisation.




Cross-section image of multiple beads in a narrow-groove weld.

The challenge lay in developing a robust and flexible system that could withstand the harsh electromagnetic conditions generated by the welding rig. Sensors had to be able to tolerate many kilovolts due to arc strike, yet be sensitive enough to measure changes of a few millivolts, and equally small changes in current.

After extensive tests to identify the best sensors for the job, the pilot system was integrated into the Simple demonstrator on the Nuclear AMRC's Polysoude welding cell. The sensors were packaged into a robust housing to allow them to be connected in line with the power supply and the gas tungsten arc welding torch.

The team successfully tested the monitoring system through a series of welding trials, from single beads to multiple passes to fill a thick-section narrow groove typical of joints for the nuclear industry.

The collaboration allowed the ESIM team to understand in greater detail the requirements and limitations of a viable commercial product, and to refine the potential specifications of such a device.

Additional development will be required to establish a statistically valid baseline in terms of an arc-stability profile, and to understand how welding process defects can be classified according to the in-process data.

# Acoustic sensor

Lead partner: **Nuclear AMRC**

**With careful analysis, the sound of a welding process can reveal the presence of welding defects and other problems.**

Arc sound contains a wealth of information about the welding process, such as the behaviour of the arc column, the behaviour of the molten metal, and the metal transfer mode. Expert manual welders can instinctively use acoustic and visual feedback to help them monitor and control the process, and studies have shown that weld quality can suffer significantly in the absence of sound.

For automated welding processes, live acoustic analysis based on machine learning systems offers a relatively easy, low-cost and flexible solution for process monitoring.

Previous research has shown that acoustic monitoring can work in the laboratory, but industrial environments throw up additional challenges thanks to noise from other machines and workshop activity.

We used two microphones – one positioned close to the weld head to record the sound of welding, and one further back on the welding rig to record ambient noise. Processing the synchronised signals to subtract one from the other produced a good recording of the welding process.

Characterising the signal requires statistical analysis of the signal in both the time and frequency domain.

We used recorded data from a series of welding runs to train the machine learning system, using the outlier detection technique to identify acoustic anomalies which could relate to potential flaws. This technique avoids the need to simulate deliberately defective welds.

The research demonstrated that acoustic monitoring is a valid method of real-time process monitoring, which can potentially save a significant amount of inspection time and cost, and build confidence in the welding process. It is relatively cheap and easy to install, making it an attractive option for SMEs.

Further development is needed to test this approach on different welding processes in different environments, and to build a database of industrial welding sounds to train and test a machine learning prediction system.

# Visual monitoring

Lead partner: **TWI**

Continuous visual inspection of a weld process can provide a wealth of information and reduce the risk of defects.

Currently, weld monitoring depends on the operator observing the weld, either directly through a filter or from a screen linked to a camera close to the welding head. As this requires constant attention and relies on the expertise of the individual operator, it's far from ideal, especially for large thick-walled components where welding can continue for several hours.

The visual data collected by a camera can instead be fed into an automated system for analysis through algorithmic processing of the digital signal. This system would continuously watch the welding process and determine if it was optimal or non-optimal.

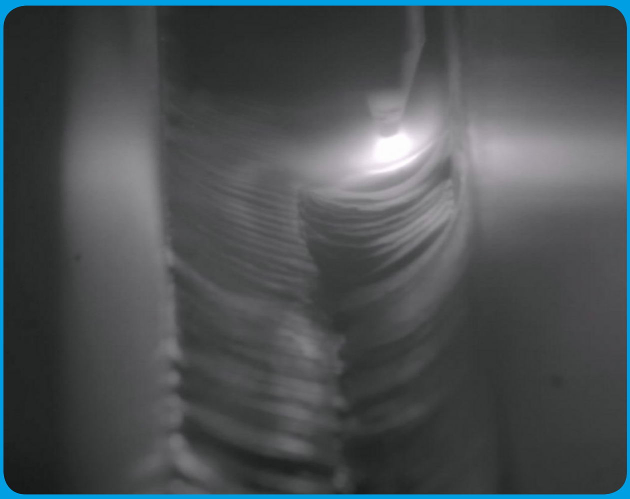
For the Simple project, image analysis is performed using neural networks. Each image or video frame is analysed using an image recognition algorithm to segregate it into a set of pre-determined categories. These are based on the conditions that an operator would potentially observe, such as optimal welding, lack of fusion, or burn-through. If a specific number of non-optimal categorised frames are detected, the welding process can then be interrupted.

The TWI team used off-the-shelf components, including a Xiris XVC1000 camera, and constructed a software framework that could decompose the videos into individual frames, generate a neural network to analyse the frames, and then categorise the information.

To train the neural network, the team recorded a series of welding trials on the Nuclear AMRC Polysoude cell, selectively varying the welding parameters to produce intentional defects with known causes. Several hundred videos were recorded in four phases, totalling several hundred thousand individual frames or images. Around a quarter of the frames were reserved for testing the neural network, following training on the bulk of data.

The system showed some success in accurately detecting the presence or absence of defects, proving the concept of the approach, but needs further development to meet an acceptable industrial level of accuracy. Development is also needed to allow live image analysis for in-process monitoring.

The Simple collaboration focused on narrow-groove gas tungsten arc welding. Early trials at TWI have shown promising results in other processes including thin-sheet and gas metal arc welding.



Example still from the Xiris camera.

# Technology demonstrator

Lead partner: **Nuclear AMRC**

**To prove the viability of the Simple integrated welding and monitoring tool, we created a single technology demonstrator using all the sensors and monitoring tools which had been developed to an adequate level of readiness.**

The acoustic, vision and laser sensors, as well as the power monitoring and synchronised data collection systems, were integrated with the Nuclear AMRC's Polysoude NG-8-300 gas tungsten arc welding cell.

The ultrasonic and interferometry tools are still at an earlier stage of technology readiness, and were not included in this initial demonstrator.

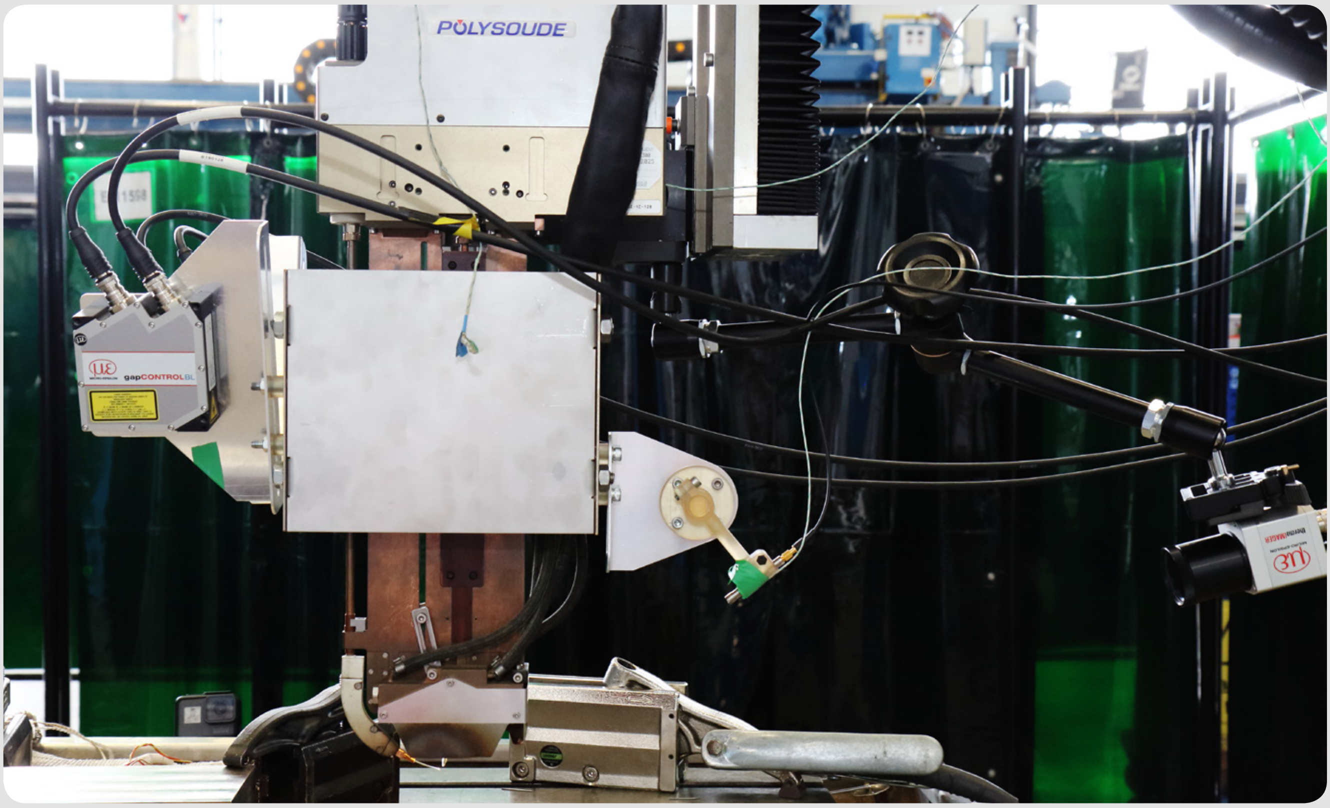
We worked closely with Polysoude, a tier two member of the Nuclear AMRC, to design the fixturing to hold the sensors around the weld head.

To develop the sensor fixturing without having to book the welding cell for long periods of unproductive time, we used a CAD model provided by Polysoude to produce a 3D-printed replica of the welding head. We also printed a replica of a representative narrow-groove weld geometry to assist with the positioning of the visual and laser sensors.

Total weight of the system had to be less than 10kg, to ensure the welding head could still be manipulated with sufficient accuracy.

To keep the technology as relevant as possible, we ensured that it was fully transferable to any other relevant welding system.

After transferring the sensor fixturing to the real Polysoude, the complete system was tested with a series of welding trials. Trials involved narrow groove welds of



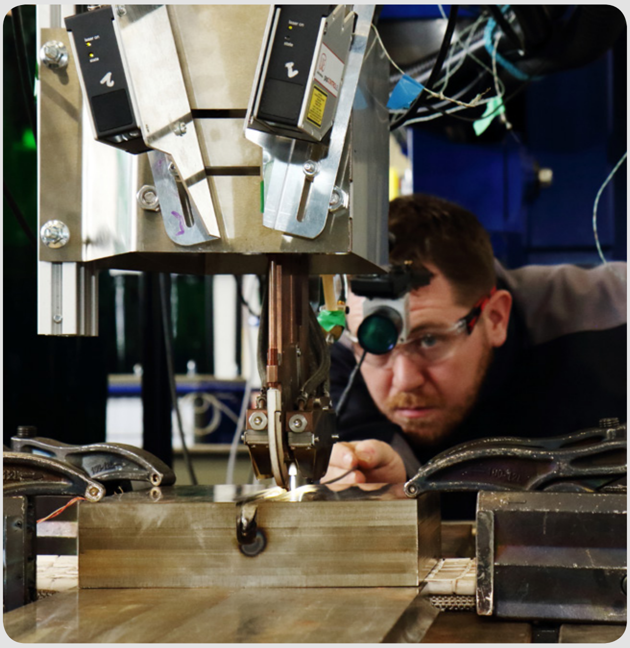
The Polysoude welding head with laser, acoustic and visual sensors.

up to 50mm thickness in SA508 steel representing thick section welds of nuclear pressure vessels.

The prototype system successfully gathered, displayed and recorded synchronised in-process data from all sensors in real time. The trials included intentionally flawed welds, allowing the data to be correlated against known defects.

Further work is required to develop this first prototype, including further trials on representative-scale components, and development of industrially-acceptable process control systems to allow full automation.

Ultimately, with continued development of all the featured sensor technologies, we aim to design a fully integrated welding and inspection tool which can be seamlessly deployed on a single-platform manufacturing platform as one of a comprehensive choice of end effectors.



Preparing the demonstrator for a welding trial.


A 3D-printed replica of the Polysoude welding head used to optimise sensor positioning.

# Laser sensor

## Lead partner: **Nuclear AMRC**

**Laser sensors can accurately record the topology of a complex surface by analysing the reflection of a projected laser line, and calculating the distance to each point along the line. In welding applications, they can detect abnormalities and defects on the weld surface.**

In this part of the Simple project, we investigated a high-speed laser scanner system to evaluate a weld process in real time and identify potential defects.

We selected low-cost lightweight Micro-Epsilon sensors which can work effectively at temperatures up to 60°C.

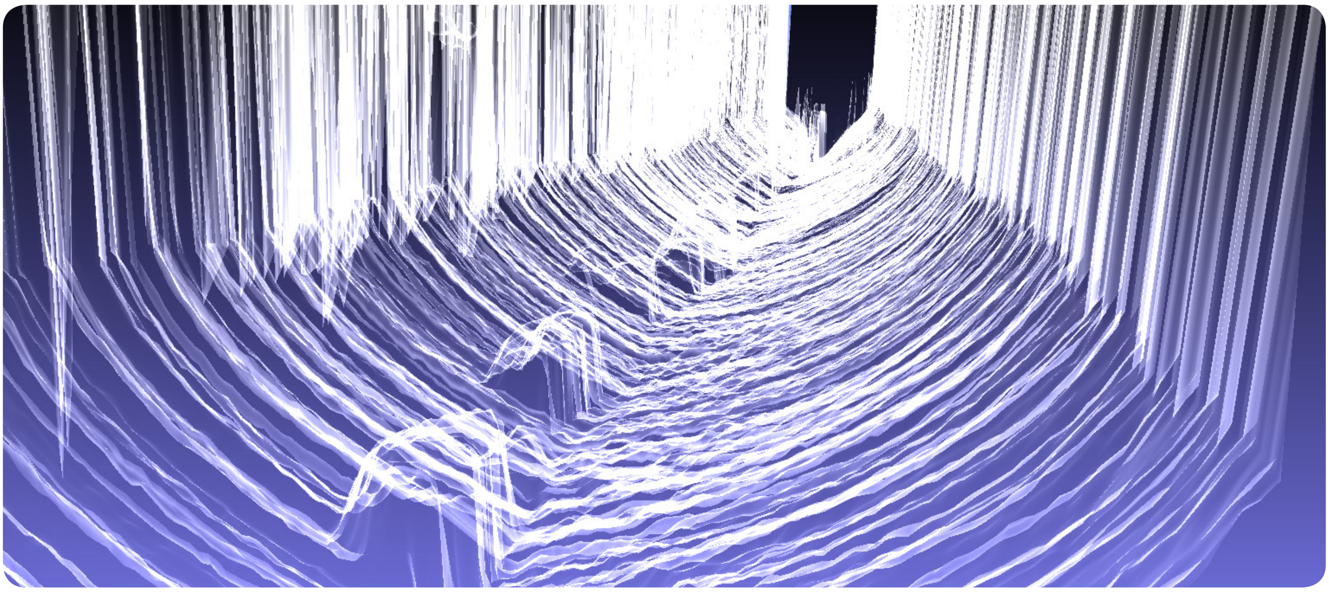
The geometry of the narrow groove join meant that a clear view of the entire weld can't be achieved with a single sensor. We investigated the use of two sensors to give a more comprehensive view. The dual sensors were inversely synchronised, to avoid the laser light from one being picked up by the other, and attached to the welding head with an adjustable bracket so their combined field of view could be optimised for different groove geometries.

In initial trials, we achieved good results with a 3D-printed replica of a typical groove, but experienced significant noise and distortion in the data from a metal joint. These are caused by reflections from the walls of the groove, and are more of a problem when the sensors are at an angle to the workpiece. We found that a single sensor in a perpendicular position actually provided better quality data than could be achieved with dual sensors.

We continued trials with a single sensor, and used an additional data processing algorithm to remove the effects of reflections. This allowed us to extract the desired geometric information, using a LabView program to examine the data in real time with good results.

While this initial project used off-the-shelf scanners, accuracy could be improved by the development of a bespoke system.

The technique can also be developed for other applications, and we have carried out successful initial trials with wire-arc additive manufacturing processes using dual laser scanners.



Laser scan of a groove, showing weld spatter.

# System integration

## Lead partner: University of Sheffield AMRC

**For effective in-process monitoring, you need to capture the data produced by all the various sensors in a variety of formats, integrate and synchronise in real time, and store for later analysis.**

Design and prototyping engineers at the University of Sheffield's Advanced Manufacturing Research Centre (AMRC) successfully demonstrated a system to integrate all the selected sensor technologies with the welding hardware and software, and allow recording, analysis and export of all the data types.

The AMRC team considered a number of off-the-shelf platforms, including technology used in the automotive industry for real-time vehicle testing, which could be customised for the particular needs of the Simple project.

The system was designed to be scalable to allow additional data streams to be integrated, and to allow additional functionality such as real-time analytics and closed-loop control.

The team designed and built a freestanding cabinet to contain all the hardware for the platform, including a set of three screens to provide a live display of key data streams and video of the welding process.

The platform has enough processing power to run machine learning algorithms, potentially in real time, to provide improved quality monitoring and parameter optimisation. With further development, it could offer real-time closed-loop process control based on live input from the full range of sensors and monitoring tools.

Three screens show live data and video.

# Ultrasonic sensor

## Lead partner: **University of Strathclyde & Peak NDT**

**Ultrasonic inspection is an established technique for ensuring the integrity of completed welds, allowing the identification of defects beneath the surface of the weld.**

Ultrasound can also be used for in-process monitoring of weld quality, but the high heats and steep temperature gradients caused by multi-pass welding present major challenges. The speed of sound through a medium changes with its temperature, leading to defocusing and beam bending. High temperatures can increase the effects of electronic thermal noise from the welding rig, limiting the sensitivity of the sensor.

In-process inspection also presents additional challenges compared with inspection of complete welds, with a much higher risk of false positives caused by echoes from unwelded surfaces.

High-temperature array assemblies suitable for live weld inspection are currently under development at the University of Strathclyde and elsewhere, but are still at an early stage of technology readiness.

The Strathclyde team investigated a selection of commercially-available ultrasound arrays designed for inspection of completed welds, to see if they could be adapted to meet the needs of the Simple programme. The team ran initial trials with an array produced by Peak NDT on a Kuka robotic welding cell at the University of Strathclyde, with the sensor results compared with inspection of the completed weld.

The research confirmed the feasibility of the approach, and the team identified the most promising technologies for further development. The researchers also developed a proposed process for in-process ultrasonic inspection of multi-pass welding which can minimise the problems caused by high temperatures.

Further work will be needed to verify calibration and detection for the full range of possible weld defects, and to automate adaptive correction for thermal effects.

The same approach could also be developed for other welding configurations such as pipeline welding, as well as wire-arc additive manufacturing processes. The University of Strathclyde's Advanced Forming Research Centre (AFRC) is commissioning a new wire-arc additive cell which could be used to develop in-process ultrasonic inspection.


A Peak NDT ultrasonic sensor with a sample weld.

# Electronic speckle pattern interferometry

Lead partner: **Nuclear AMRC**

**Electronic speckle pattern interferometry (ESPI) is an emerging sensor technology which can measure the deformation of a welded area at nanometre levels of resolution, helping predict weld performance.**

Our initial analysis for Simple highlighted the requirement for a measurement instrument which can rapidly analyse distortion caused by weld heat, and provide a high-resolution three-dimensional measurement of the surface around the weld.

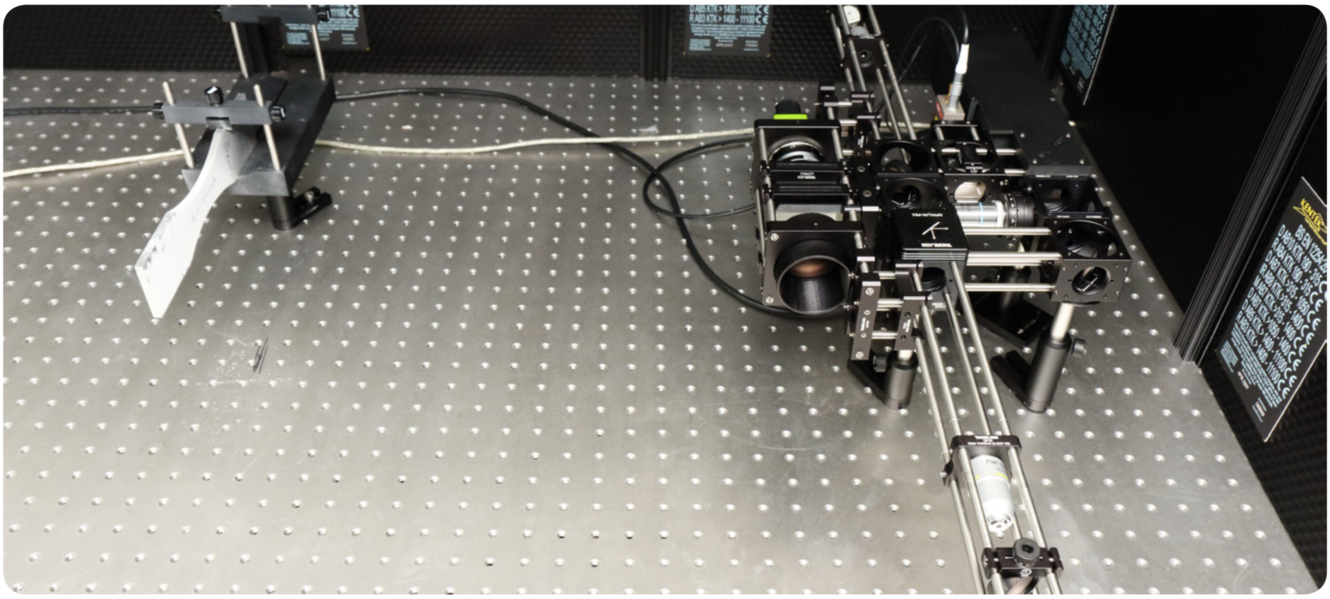
In essence, the ESPI technique projects coherent laser light onto a surface, and then records the reflected light. Any roughness of the surface creates a pattern of light and dark speckles caused by interference between the reflected and scattered light wavelets. This pattern can then be analysed to precisely map the surface.

Commercially available systems can rapidly map areas from five centimetres to one metre square at nanometre-scale accuracy. This is around 100 times more sensitive than laser scanning.

We found that no commercial systems met the requirements of the Simple project, so we designed and built a bespoke prototype system to provide full control over the experimental process. We used a combination of off-the-shelf optical and electronic components and bespoke 3D-printed mounts, with LabView and Matlab software for image processing and analysis.

In initial trials, the prototype system accurately measured distortion in the x-y plane of the surface, proving the concept of ESPI for this application.

Further development is needed to develop the technique for industrial use, and to miniaturise the hardware for integration within a welding head.



The prototype ESPI sensor used for benchtop trials.

# Dissemination & business engagement

Results from the Simple programme were shared with the UK's nuclear manufacturing supply chain throughout the project.

## Showcase events

The Nuclear AMRC organised two industry-focused events to showcase Simple and other projects funded by the Nuclear Innovation Programme (NIP).

By organising events covering a range of NIP projects, we were able to maximise our audience, and highlight complementary research and collaboration opportunities.

In January 2019, we hosted a special meeting of the Nnuman community, an industry-led forum to support the development of the next generation of nuclear technology. The community was established in 2018 as a continuation of the technical advisory board for the EPSRC-funded Nnuman (New Nuclear Manufacturing) programme.

The Nnuman seminar at the AMRC Knowledge Transfer Centre discussed projects from across the advanced manufacturing and materials strand of NIP, and was attended by over 75 members of the nuclear R&D community.

We also organised the Nuclear Innovation UK conference in July 2019, a major industry conference presenting research from all strands of the NIP. The two-day conference in Sheffield brought together around 275 delegates from industry and academia, and included technical presentations on Simple from the Nuclear AMRC's Matt Smart, plus an opportunity to visit our workshop to see the technology demonstrator in action.

The technology demonstrator has also been presented to many other industrial and academic visitors to the Nuclear AMRC – our research factory in Rotherham welcomes around 10,000 visitors a year.

## Conferences

Researchers from the Nuclear AMRC and partners presented their work at industrial and academic conferences worldwide, including:

- ASME Pressure Vessels and Piping 2018 (Prague, Czech Republic).
- National Structural Integrity Research Conference 2018 (Cambridge UK).
- 13th International Conference and Exhibition on Laser Metrology, Coordinate Measuring Machine and Machine Tool Performance (Rotherham, UK).
- ASME International Conference on Nuclear Engineering (Tsukuba, Japan).
- International Congress on Welding, Additive Manufacturing and Associated Non-destructive Testing (Metz, France).
- 72nd International Institute of Welding Annual Assembly (Bratislava, Slovakia).
- American Welding Society Annual Conference 2019 (Chicago, US).

We also held regular consortium meetings with all partners and stakeholders – including BEIS and the Nuclear Innovation Research Office – to share the latest developments and ensure consistent delivery of the Simple programme.


Delegates at the Nuclear Innovation UK conference visit the Nuclear AMRC workshop.

## Publicity

Alongside the dissemination events, we promoted and shared the Simple project with our wider supply chain audience through a variety of communication channels including the quarterly *Nuclear AMRC News*, online and social media.

A dedicated page on the Nuclear AMRC website featured regular updates, plus a short video showing welding trials with the technology demonstrator: **namrc.co.uk/services/crd/simple**

Articles were placed in key industry titles including *The Manufacturer* and *Nuclear Engineering International*. And, in a joint entry with the Inform project, the Simple team were shortlisted for *The Engineer* magazine's Collaborate to Innovate Awards 2019.

Press announcements were also shared through our network of stakeholders, including the University of Sheffield and High Value Manufacturing Catapult, to maximise our reach.

Researchers from all partners continue to publish research papers based on their Simple work through a variety of academic publications.

# Partners

The **Nuclear Advanced Manufacturing Research Centre** helps UK manufacturers win work in the nuclear sector. We work with companies of all sizes to develop new technical capabilities, raise quality and reduce risk.

The Nuclear AMRC is backed by industry leaders and government, and is part of the University of Sheffield and the High Value Manufacturing Catapult.

namrc.co.uk

**Peak NDT** is a high-end technology company specialising in the development, manufacture and support of multichannel and phased array ultrasound controllers for non-destructive testing. Peak NDT also provides consultancy services including feasibility studies, technique development and ultrasonic inspection modelling.

www.peakndt.com

**TWI** is a membership-based organisation, supporting individuals and companies alike. It is one of the foremost independent research and technology organisations, spanning innovation, knowledge transfer and problem resolution across all aspects of welding, joining, surface engineering, inspection and whole-life integrity management.

www.twi-global.com

The **Enabling Sciences for Intelligent Manufacturing** (ESIM) group at the University of Sheffield's Department of Physics and Astronomy works with industry to solve manufacturing problems using groundbreaking research in the areas of applied physics, engineering, and robotics.

esim.ac.uk

The **Advanced Manufacturing Research Centre** specialises in world-leading research into advanced machining, manufacturing and materials of practical use to industry. It is part of the High Value Manufacturing Catapult and the University of Sheffield.

www.amrc.co.uk

The **University of Strathclyde** is a leading international technological university, with a strategic focus on advanced manufacturing and materials. It is home to the Centre for Ultrasonic Engineering and the Advanced Forming Research Centre, part of the High Value Manufacturing Catapult.

www.strath.ac.uk

# Next steps

In the first phase of Simple, we produced a technology demonstrator featuring four discrete sensor systems integrated into one common platform, each providing valuable information for process control in close to real time.

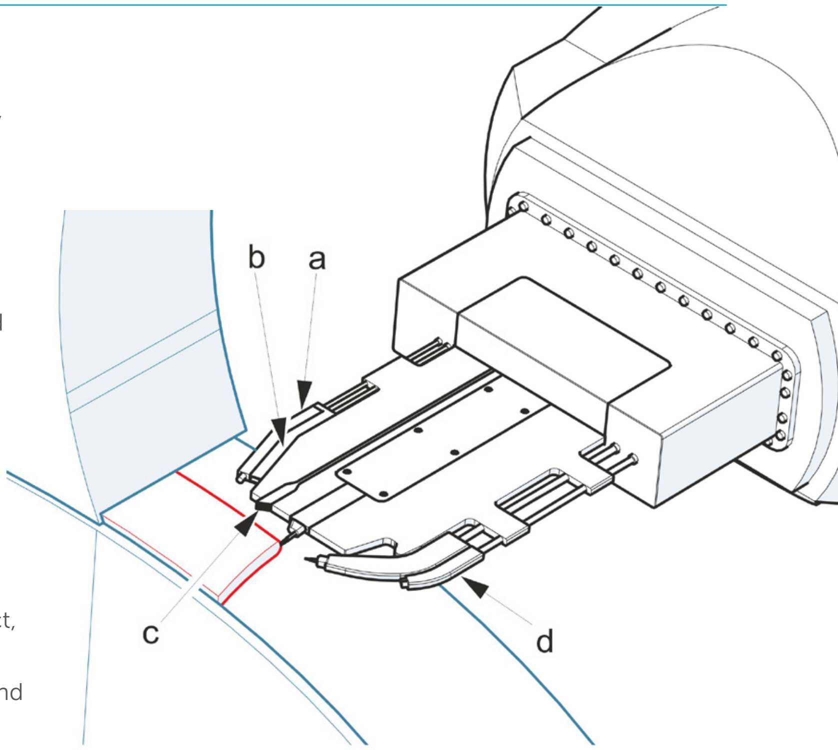
We have shown that this information can be correlated with conditions that lead to welding imperfections.

Further work is required to develop the analysis methods to meet the requirements of full autonomy. This summary report identifies potential routes for continued near-term development of each of the technologies.

In the medium term, we propose to develop a compact, fully-integrated welding and inspection tool featuring miniaturised and optimised versions of all the sensor and control technologies. This will be tested on one of our large machining platforms to prove the Simple concept of single-platform manufacturing.

Longer-term development could then integrate this tool with a comprehensive selection of machining, cladding and inspection heads on a single manufacturing platform.

By combining a full range of conventional and advanced techniques onto a single platform, we can achieve the Simple vision of reducing production cost and time for a range of complex fabrications by at least 50 per cent. This will give UK manufacturers a sustainable competitive advantage, and reduce the cost and risk of future nuclear technologies.




Concept design for a fully-integrated welding and inspection tool.

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CATAPULT
High Value Manufacturing

Working with
Innovate UK

## Project partners

PEAK NDT

TWI

The University Of Sheffield.

AMRC
ADVANCED MANUFACTURING RESEARCH CENTRE

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