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Underpinning UK High-Value Manufacturing: Development of a Robotic Re-manufacturing System

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***Abstract*—Impact and its measure of outcome is a given performance indicator within academia. Impact metrics and the associated understanding play a large part of how academic research is judged and ultimately funded. Natural progression of successful scientific research into industry is now an essential tool for academia. This paper describes what began over ten years ago as a concept to automate a bespoke welding system, highlighting its evolution from the research laboratories of The University of Sheffield to become a platform technology for aerospace re-manufacturing developed though industry-academia collaboration. The design process, funding mechanisms, research and development trials and interaction between robotic technology and experienced welding engineers has made possible the construction of a robotic aerospace turbofan jet engine blade re-manufacturing system. This is a joint collaborative research and development project carried out by VBC Instrument Engineering Limited (UK) and The University of Sheffield (UK) who are funded by the UK governments' innovation agency, Innovate-UK with the Aerospace Technology Institute, the Science and Facilities Technology Council (STFC) and the Engineering and Physical Sciences Research Council (EPSRC).**

Keywords—Robot; Welding; Manufacturing; Academia

I. INTRODUCTION (MANUAL SYSTEM AND THE UNDERPINNING TECHNOLOGY, HOW THE CONCEPT DEVELOPED)

Based at CERN, the European Organization for Nuclear Research, the Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator. The Nobel Prize winning ATLAS Experiment is one of two general-purpose detectors at the Large Hadron Collider. It investigates a wide range of physics, from the search for the Higgs boson to extra dimensions and particles that could make up dark matter. At 46 m long, 25 m high and 25 m wide, the 7000-tonne, 100m below ground ATLAS detector is the largest volume particle detector ever constructed [1], [2], [3], [4], [5], [6], [7], [8], [9].

Construction of the various detector sections of ATLAS took place from 1997 to 2009 [10], The University of Sheffield (TUoS) is heavily involved with the construction, and installation and later operation of the Inner Detector (ID) particularly the cooling systems. Sharing a number of design philosophies with aerospace, defence and space science, particle detectors require light-weight materials with high strength. From 2025, the LHC will be upgraded to allow it to achieve a factor of 10 luminosity increase (higher rate of collisions) essential for probing new physics phenomena in the future. The route to High Luminosity LHC (HL-LHC) involves various ATLAS detector upgrades and requires significant infrastructure changes beginning in 2017.

The original ATLAS ID cooling system had thousands of tube and pipe connectors, all a potential single point of failure for the detector and source of high materials mass [4], [11], [12], [13], [14]. For the future ATLAS Upgrade Inner Tracking Detector (ITk) it was desirable to make the cooling connections more robust and in order to compensate for higher luminosity, further reduce material mass or weight. Removal of the connectors and tube joining methods by welding was studied resulting in the need for some form of in-situ welding system for ultra-thin wall tubing connections. Well before any formal funding was received, research into a high reliability cooling system for the UK-ATLAS Upgrade project began by analyzing Space Agency documentation [15], [16]. These paper study launched a sizeable market survey and later, manufacturers test-piece weld trials using commercial welding equipment (conducted from '05-'06). This highlighted that no commercially available welding system was proven capable of joining ultra-thin wall (200um) 316L stainless steel tubes, the chosen ATLAS ITk prototype tubing material.

VBC Instrument Engineering Limited (VBCie), a UK SME, produced in 2006, a unique gas tungsten arc welding (GATW) power source named the InterPulse HMS system. This system was first demonstrated at the ESSEN Welding Fair, (Germany 2006). Publicity from this demonstration brought the power supply to the attention of UoS researchers as its specification solved many issued highlighted as "troubling" from previous research papers. This welding power supply was heavily adopted and utilized by the aerospace and power generation industries and a demonstrator was available. Our simple concept was to add automation to the InterPulse by means of an orbital weld head. Orbital GTAW or Tungsten Inert Gas welding (TIG) was well established in the 1960s and the technology advanced by the space race. Numerous failures in space vehicle propulsion fuel systems, failed welds [17], [18] and subsystem electronic component damage [19], [20], [21], [22], [23], [24], [25], [26], [27] induced from stray electrical arcs all looked to be avoidable. The journey from concept to improve detector construction to later a full joint technology development programme was underway with a simple, "yes we can do it" from the VBCie Directors.

The UK manufacturing sector has been rejuvenated largely due to a focus on high value manufacturing. However, to maintain a global competitive advantage the UK Government has identified the need for continued research effort to develop

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the next generation of advanced manufacturing. One direction that has huge potential is highly reconfigurable and flexible manufacturing systems and their application to the aerospace industry. Predictable re-manufacturing processes help manufacturers reduce waste (salvage during manufacture) & offer raw material reduction. Minimizing production downtime (productivity of repair techniques) and repair costs (cost of repair is generally the less important factor when considering repair, time to repair is the more important consideration).

Working with industry must allow considerable understanding of the project and partners requirement to gain a commercial advantage. Within the MRO (Manufacturing, Repair and Overhaul) industry, current repair techniques rely on significant elements of manual welding. Aerospace turbine compressor blade remanufacturing sites generally consist of over 40 highly skilled welders per site running a shift pattern supported by ancillary staff support to move parts around the repair facility contributing to a huge overhead. Current remanufacturing is only able to be carried out on recovered blades from a serviced aero engine which is 80% of repairable blades. The actual yield figure of the compressor blades which are successfully repaired by the manual process is approximately 45% which is largely attributed to human errors in the process. The proposed system is designed to recover a 100% yield. In cash value, a repair is worth from £250 to £7k dependent on size & material. For example, A Rolls-Royce Trent 1000 has ~600 blades so extending blade life represents large savings to both aero engine manufacturers & airline operational costs.

TIG welding has often been considered a "dark art", successful welds are often made by highly skilled welding engineers who rely purely on experience and personal ingenuity to solve welding problems and feel their way through a repair on the shop floor. This practice often results in one off solutions to problems that provide little empirical measurement data. Human error, repetitive strain injury and loss of production control are avoidable through implementation of robotic systems.

There is now a real global shortage of highly skilled engineers. The Perkins Review of UK engineering skills [41] indicates that recent results “will not pay off … delivering in ten to fifteen years”. Automated welding solutions reduce the need for highly skilled staff thereby allowing manufacturers to invest in future engineers. Automation allows manufacturers, who have a professional responsibility for safe operation, to site equipment geographically where labour is cheaper & skill sets potentially lower.

In the following text, we will describe the methodology our partnership and research group has followed over the past 10 years through development of welding systems for ultra-thin wall tubes (Section II), project description of the development of a machine vision system for monitoring and inspection of welds (Section III), project description of an autonomous aero turbine blade re-manufacturing system (Section IV), simulations of robots for welding and pick–and-place (Section V), and the development of non-destructive testing and data acquisition system for ultra-thin advanced aerospace alloy joining using automated constricted gas tungsten arc (Section VI). One key factor that allowed longevity and continued innovation from this partnership was the mutual benefits gained from jointly developing new technologies.

II. Methodology (How We Have Developed the Welding System for Ultra-Thin Wall Technology)

Experienced welding engineers use their knowledge and apply their skills almost automatically by subtly fine tuning multiple welding control parameters to achieve the required results. Their dynamic inputs alter the weld deposition characteristics such as; size, shape, depth & micro-structure. The variable parameter changes are termed CLAMS (current, length, angle, manipulation and speed). CLAMS detailed in a welding procedure schedule or documents are used to provide numerical input for the manual operator to achieve correct results with high yield.

Automated repetition of CLAMS data enables production of the correct weld deposition with high repeatability but with the inability to respond to a change in dynamics or conditions. True response requires intelligence which has proven exceptionally challenging to develop when welding complex profiles (curves) and super alloy materials (heat input & distortion) now utilized by aerospace engine manufacturers with the GTAW technique [17], [18].

Development of any advanced, intelligent robotic welding system requires correct interrogation of welding parameters and output. Advanced programming of robots, data interpretation from associated sensory and feedback systems are required to mirror human input. Using process analysis to determine stimuli, replacement of human sensory receptors with electronic sensors, vision systems and high speed data acquisition and control systems allows for the intelligent fine tuning of multiple welding parameters at any one time.

The scope of the projects has not followed a linear or obvious pathway. The cyclic nature of the western world economies, large manufacturer’s response to investment and subsequent capital expenditure show a wave like effect on how industry/academic research projects slow and expand. Figure 1 outlines the relationship and project development timeline from first requirements for an alternative to joining ultra-thin tubes for the next LHC upgrade, until the development of intelligent robotic remanufacturing solutions for aerospace and nuclear sectors.

With a known requirement in 2006, the goal was clear. However, the technology was simply not available. A considerable amount of research was conducted analysing specifications of COTTS technology. Fortunately, a combination of knowhow from Sheffield [4], [13], [28], [29] and technology from VBCie [14] provided a theoretical solution. The following four years refined project ideas as the technology matured. By 2010, research funding concepts were made, and 2011 realised the construction of the initial demonstrator funded by the STFC Innovations and Partnerships Scheme. Progress was made with parallel investigations on the ATLAS Upgrade Experiment both in the UK and CERN, investigating the use of ultra-thin stainless steel tubing for cooling systems. Realisation quickly matured and these techniques for orbital welding of stainless steels could be easily transferred to titanium alloys.

This revolutionised the approach of our project and allowed entry into the aerospace domain.

III. Machine Vision for Welding

A. Project Scope

The primary aim of this study was to produce a high resolution stereo camera bar system that could be integrated with a robotic welding arc enabling the monitoring and inspection of high-value aerospace parts. The system will detect the incoming parts and interface to the welding arc to ensure it is at the correct reference position. This is particularly important in the aerospace industry as most parts are custom-made, consisting of unique shapes and sizes. This means the system will detect faults and defects on the parts and determine the appropriate re-manufacturing or correction procedure required. Another aim of the project is that the vision system will detect cracks and shape deformation to provide a non-destructive method of part testing and system control.

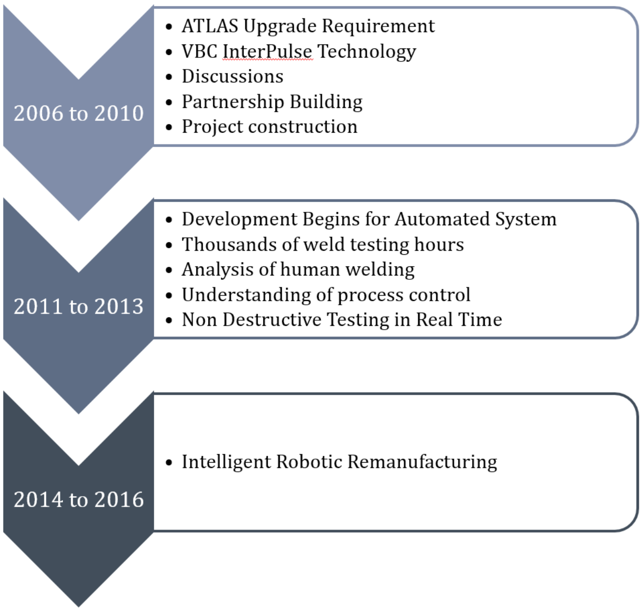


Figure 1. Project Development Timeline [30], [31], [32], [33], [34]

The technology relies on using stereo imaging pairs to produce a 3D reconstruction of the target area thereby locating it and produces its topological maps to provide information necessary for the welding to take place.

A prototype system will be built in this study which will be able interfaced to a robotic arc to prove that the system operates in a representative environment.

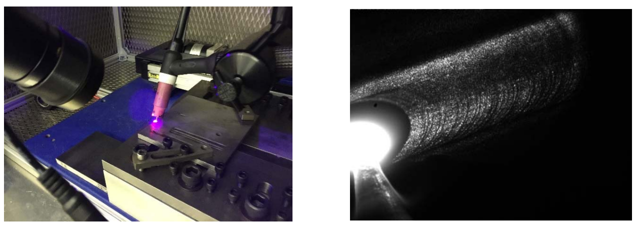
This product has great potential to be developed not only for robotic welding systems but also for other automated systems that require vision systems. A route map of commercialization will be produced in order for this product to develop into a commercial product within different industries.

B. 3D stereo vision system

One of the key aspects in achieving automation of the welding process is the visualization of the weld. A 3D stereo vision system will be used to image the welding process for monitoring and inspection purposes [35]. A camera and lens combination is chosen in order to achieve a resolution which is able to detect defects of sizes 25 µm, measure the welding process at a speed of 20 mm/s and image an 8 mm^2 area. A USB3 1.2 Megapixel camera with a 1/3 inch 3.75 µm pixel pitch global shutter CMOS sensor and a macro lens with a variable focus from 13-130 mm are used to achieve the required resolution. In addition to the cameras and lenses, an important component of the machine vision system is the illumination and filtering. Following information obtained by spectral measurements of the welding arc, a high power laser and specifically tuned laser were chosen to minimize the influence of the welding arc on the images.

Figure 2 shows a snapshot of TIG welding during the first stage testing of the vision system. The figure shows that the system is able to image the welding tip, pool and bead. Whilst this is important for testing the capability of the image system in filtering out the high intensity welding arc, the final system is planned to only image the welding pool and bead as these provide information about the quality of the weld.

The next stage in the development of the 3D stereo vision system will be to use a second camera in order to acquire the welding process simultaneously from two separate angles. The images will then be processed using a semi-global matching (SGM) stereo algorithm in order to produce a high resolution and accurate 3D reconstruction of the welding process. This will provide high resolution and accurate information for inspection and monitoring of the weld. Such information is able to be used by the welding robot in controlling the welding process by adjusting parameters such as voltage intensity, distance between the arc tip and sample and welding speed.



a) b)

Figure 2. Vision system on a) arc strike and snapshot of b) weld pool

IV. Autonomous Aero Turbine Blade Re-Manufacturing System

A. Project Scope

VBC Instrument Engineering Limited in partnership with Sheffield University have been awarded funding and support from Innovate UK to work on a project to design and manufacture an Autonomous Aero Turbine Blade Re-Manufacturing System which aerospace industry deals with MRO (Maintenance, Repair and Overhaul) in relation to the blade repair systems for their turbine engines. VBCie are well placed to allow UK representation in this growing market and if successful will make the UK world leaders in this field.

In short, high value aerospace gas turbine blades are subjected to extreme temperatures during operation, resulting in wear. Approximately after 30,000 hours of air time, engines are entirely overhauled, the blades are taken out and repaired using manual weld deposition then refinished. Major problems have been identified through errors in the weld build-up process. Half of all blades are reclaimable, although current yield is only around 80 per cent of that half owing to high heat input during welding and poor practice.

Investigations into the automation of the GTAW (Gas Tungsten Arc Welding) process for turbofan compressor blade re-manufacturing have demonstrated that highly skilled welding engineers are required to carry out what is perceived to be a simple task. Through the use and interconnection of multiple systems and high speed electronic data interchange, the highly skilled task can be replicated autonomously.

The objective of this industrial research project is to provide a turnkey automated solution that identifies both wear on the blade and carries out a low heat input weld build up, potentially doubling existing service life. The autonomous system will provide wear data from a scanning system allowing a repair to the specific area only as real-time welding evaluation data is applied to NDT using a novel technique [36], [37] to increase throughput and save the scrapping of blades. VBCie's Inter Pulse technology is ideally suited to any application that benefits from low heat input. This data can be fed back to the manufacturer to further both service life, design and efficiency.

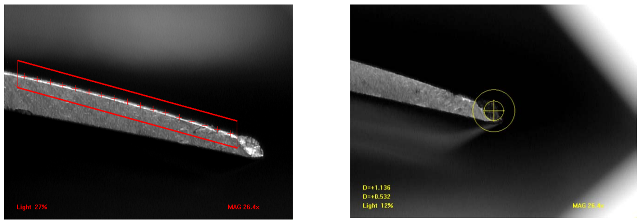
B. *Aerospace turbofan compressor blade image analysis and processing*

Edge detectors and derivative techniques, such as rakes, concentric rakes, and spokes, locate the edges of an object with high accuracy. Edge detection is an effective tool for many machine vision applications because it provides information about the location of the boundaries of objects and the presence of discontinuities. Edge detection will be used in the image analysis of turbofan compressor blades in the following areas: gauging, detection, and alignment (see Figure 3).

Gauging can determine if the blade under inspection is manufactured correctly. The part is either classified or rejected, depending on whether the gauged parameters fall inside or outside of the tolerance limits. Figure 3a shows how edge detection is used to measure the length of a blade.

Detection helps to determine if a defect is present using line profiles and edge detection. An edge along the line profile is defined by the level of contrast between background and foreground and the slope of the transition. Using this technique, the number of edges can be counted along the line profile and compare the result to an expected number of edges.

Alignment determines the position and orientation of a blade. to be inspected because it may be at different locations in the image. Edge detection finds the location of the blade in the image before an inspection is performed, so that only regions of interest can be inspected (see Figure 3b). The position and orientation of the blade can also be used to provide tracking feedback to the manipulator, such as the UR5 robot, see Section V.



a) b)

Figure 3. Edge detection is used to determine the position and orientation and to detect cracks or defects of blades

V. WELDING ROBOT SIMULATION

A. *Robot algorithm development*

The robot simulator V-REP, with integrated development environment, is based on a distributed control architecture: each model can be individually controlled via an embedded script, a plugin, a ROS node, a remote API client, or a custom solution. All these make V-REP very versatile and ideal for simulating the UR5 robot manipulator from Universal Robots [38]. Control algorithms can be written in C/C++, Python, Java, Lua, MATLAB, Octave or Urbi. V-REP's applications include: fast prototyping and verification, safety monitoring and fast algorithm development.

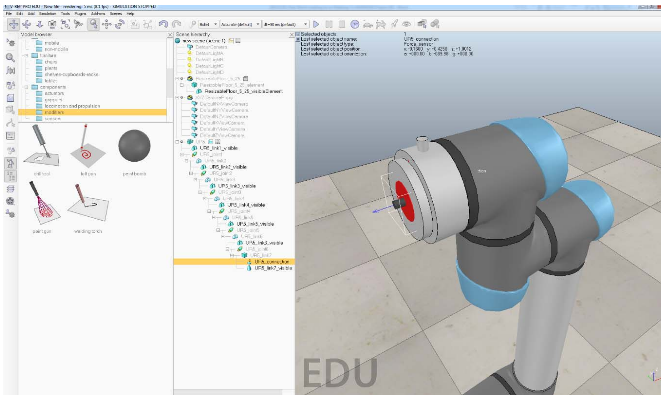
Moreover, V-REP's motion planning module allows handling motion planning tasks for kinematic chains. A motion planning task allows to compute a trajectory (usually in the configuration space of the manipulator) from a start configuration to a goal configuration, by taking into account the manipulator kinematics, joint limits and collisions between manipulator and obstacles. When the goal configuration is not directly known, it needs to be computed from a goal pose (i.e. the position and orientation in Cartesian space of the end-effector).

Figure 4 illustrate how different end-effectors such a welding torch can be chosen in V-REP simulator and attached to the UR5 robot.

B. *ROS-Industrial for Manufacturing*

ROS, an open-source project, provides a common framework for robotics applications and is heavily utilized by the research community for service robotics applications it can also be applied to other application areas, including industrial robotics for manufacturing. ROS capabilities, such as advanced perception and path/grasp planning, can enable industrial robotic applications that were previously technically infeasible or cost prohibitive.

ROS-Industrial is an open-source project that extends the advanced capabilities of the ROS software to manufacturing. ROS-Industrial benefits include, custom inverse kinematics for manipulators, including solutions for manipulators with six degrees-of-freedom such as the UR5 robot. This simplifies robot programming to the task level by eliminating path planning and teaching, optimal paths are automatically calculated given tool path waypoints. Applying abstract programming principles to similar tasks (useful in low-volume applications or with slight variations in work pieces) reduces costs. The use of open-source licenses (i.e., BSD and Apache 2.0 licenses) allow commercial use without restrictions and reduce manufacturer lock-in by standardizing robot and sensor interfaces across many industrial platforms.



a)

b)

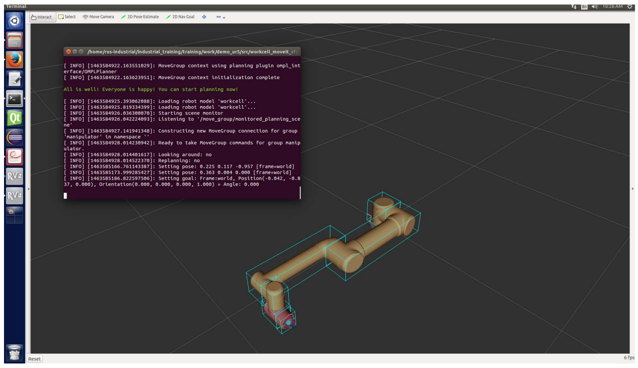
Figure 4. V-REP: UR5 Robot and welding torch simulation

Furthermore, the Universal Robot software package is part of the ROS Industrial program. It currently contains packages that provide nodes for communication with Universal's industrial robot controllers, URDF models for the UR5 robot arm and associated arm_navigation and MoveIt packages [39], see Figure 5.

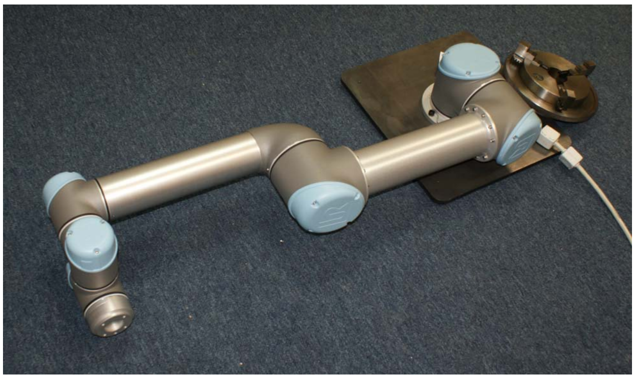
VI. Nondestructive testing and data acquisition system

A. *Ultra-thin Advanced Aerospace Alloy Joining*

The TIG Orbital Heat Management System (IP50-HMS) developed by VBCie and the University of Sheffield is a novel low-current and automatic orbital welding system. Using HMS InterPulse Technology, the IP50-HMS produces accurate narrow bead welds offering excellent weld quality and control over the weld process. The use of high frequency pulsing interposed within the pulsed weld current increases arc force and more penetration is achieved with significantly lower input current. This allows for improved heat management on critical welds whist still attaining full penetration. The machine has proven very successful in the joining of very thin wall, small diameter titanium and stainless steel alloy heat exchanger tubes. Conventional orbital welding systems cannot weld such thin wall material with small diameters. The IP50-HMS produces welded, autogenous butt joints showing higher mechanical integrity than conventional orbital welding systems evaluated. The low heat input obtained improves the materials micro-structure because of the decrease in distortion and residual stress. The IP50-HMS proves to have an exceptionally high production yield with very low weld failure rates [36].



a)



b)

Figure 5. ROS UR5 simulation in a workcell MoveIt environment

B. *Real Time measurements*

Electrical measurements of arc voltage, current and input power measurements of the VBCie system have been achieved thanks to the DAQ system developed by the University of Sheffield during the STFC funded IPS project, see Figure 6. This portable signal conditioning device is capable of measuring DC/AC welding current and voltage and can be used to evaluate fusion welding systems for Aerospace applications. The high-speed data acquisition development is also capable of multiple sensor connectivity and data capture for Civil Engineering and Geotechnical applications.

Measurements are provided in the real-time and can be used to determine if a welding tube joint is successful or not. The IPS project assessed the performance of the IP50-HMS while performing TIG orbital autogenous butt welds on tube joints in titanium and 316L stainless steel ultra-thin wall tubes. Metallographic observations performed on a ZEISS Axio Imager M2m microscope for detailed observations showed no structural or geometrical imperfections in the weld bead. Microhardness tests have also been performed according to standard BS EN 1043-2 [40]. Furthermore, calculations of heat input were obtained based on arc voltage and welding current measurements using the DAQ system for several titanium outer diameters (OD) and wall thickness sizes to allow comparison with more conventional TIG arc welds on the same materials, see Figure 7.

Figure 6. Vbc welding system and NDT DAQ

VII. TECHNOLOGY READINESS LEVELS (TRL) AND IMPACT

Industrial development supported by Research Agency funding has allowed considerable expansion of a research group at TUoS but has also built up a considerable field of expertise with regards to low heat input fusion welding, its real time inspection for defects and intelligent robotic systems to be deployed back to industry.

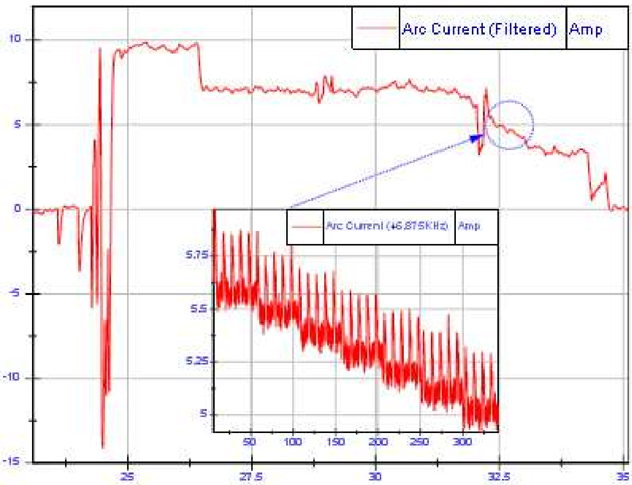


Figure 7. High speed phase current measurement

The industrial partner, VBCie has been able to gain a depth of research knowledge that would otherwise be unobtainable. The ability to try blue sky research with real projects to feed the output back into salable product development. The global MRO market is valued at £63bn and these projects have strengthened industrial relations with aerospace and the nuclear industry, see Figure 8.

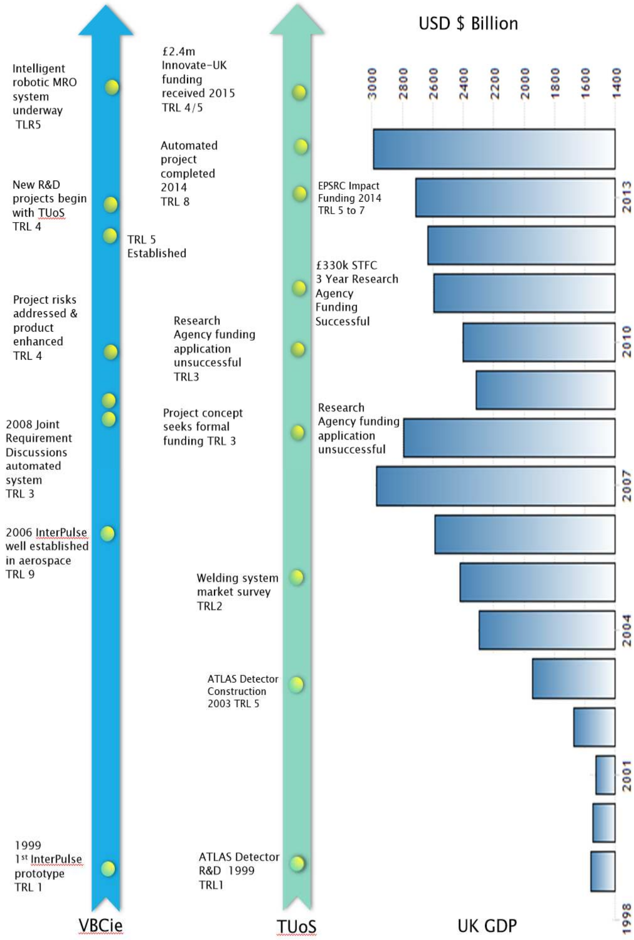


Figure 8. Project Development Timeline with UK economic GDP

Expansion to strategically locate a new VBCie subsidiary (VBCie Asia) in Singapore and the development of a network of affiliates and distributors across South East Asia better serves customers in the region. In the UK, VBCie has benefited from increasing their workforce with new engineers and general increasing of production.

New academic collaboration linking the ARTC (Advanced Remanufacturing Technology Centre) in Singapore with the University of Sheffield came about through involvement with VBCie and existing programs of research with TUoS and AStar, Singapore's research agency. This collaboration builds on existing collaborative R&D projects that both Sheffield and ARTC have with Rolls-Royce Aerospace and VBC Instrument Engineering in the UK and Singapore.

Jointly TUoS and ARTC have appointed a PhD student to address novel challenges with the remanufacturing of both large scale (aerospace) and small scale individual (ATLAS/CERN) automated low-heat welding systems. These are required for both Particle Physics detectors and aerospace applications to work with new light weight, high strength materials, such as Titanium alloys.

This research project has never proceeded in a straight line. Developing new partnerships with robotics companies, vision system manufactures and electrical test and measurement industry has increased the wealth of knowledge available to the partnership. Effectively now a highly skilled cross disciplinary team can be deployed to rapidly respond to both the needs of industry but also further academic research.

VIII. Conclusions

Construction and maintenance of an effective relationship within an academic - industry partnership is not complex when both partners drive towards a common output irrespective of motivation. The variety of knowledge, experience and skills available allow for not only exploitation but results in further avenues for technology and research development. These types of large scale funding investments do not happen overnight, they build with concepts as they mature. External factors which govern project growth demand the partnership be acutely aware of timely development of niche technologies. Economic stability and times of growth do not necessarily stop development, but slow response in line with demand. Collaborative research projects do not attract funding agency support if there is no risk of failure. Academic know-how can provide a mitigating factor to aid industrial development jointly balancing risk. Bringing a wealth of facilities, techniques and skills which increase the depth of technological development, academia is governed well by industrial desire for swift progression and return on investment. Correct exploitation from a project does follow a strategy but this strategy must be continually adapted to maintain impact and to capitalise on new research directions. The jointly developed intellectual assets and technologies within this partnership continue to expand into new areas with this specific partnership now spanning three continents, five industrial areas and the project pipeline is increasing.

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