A Robotic Re-manufacturing System for High-Value Aerospace Repair and Overhaul

Richard French[1(✉)], Hector Marin-Reyes[1], and Andrew Rendell-Read[2]

[1] The University of Sheffield, Sheffield S10 2TN, UK
{r.s.french,h.marin-reyes}@sheffield.ac.uk
[2] VBC Instrument Engineering Limited, Wellingborough NN8 6GR, UK
andy@vbcie.com

Abstract. This paper describes the necessary elements for the development of a bespoke robotic welding system for aerospace turbofan compressor blade re-manufacturing. The established industry-academia research partnership and project evolution at The University of Sheffield (UK) from 2006 is highlighted in the joint development of a disruptive platform technology for high-value aerospace re-manufacturing. The design process, funding mechanisms, research and development of key components (vision system, high-speed DAQ, advanced GTAW welding system trials) are described in this paper. Interaction of these key components when combined with novel collaborative robotic technology and experienced welding engineers has made this project possible. This industry-academia research intensive collaboration between VBC Instrument Engineering Limited (UK) and The University of Sheffield has received project funding from the Engineering and Physical Sciences Research Council (EPSRC, 2006–2010), the Science and Facilities Technology Council (STFC, 2011–2013) and Innovate-UK with the Aerospace Technology Institute (2014–2018).

Keywords: Welding · Manufacturing · Simulation · Robot

1 Introduction

The European Organization for Nuclear Research, the Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator, based at CERN. The ATLAS Experiment is one of two large scale detectors sited on the Large Hadron Collider. Sited at CERN, 100 m below ground, the ATLAS collaboration conducted the search that led to the Nobel Prize winning Higgs boson discovery in 2012. ATLAS explores extra dimensions and new particles and the detector is the largest volume particle detector ever constructed [1].

The University of Sheffield (TUoS) is heavily involved with the construction, installation and later operation of the Inner Detector (ID) of ATLAS from 1997 to date [2, 3]. To cope with the proposed High Luminosity LHC (HL-LHC) energy rate, the ATLAS inner detector now requires significant upgrades, beginning in 2017, to achieve a factor of 10 higher rate of collisions, essential for probing new physics phenomena.

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Particle detector cooling systems require lightweight materials with high strength. The existing design of the ATLAS ID cooling system included thousands of tube and pipe connectors, all a potential single point of failure and source of high materials mass for the detector [4]. 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 weight & size. A market survey conducted from 2005–2006, on commercial welding equipment highlighted that no off-the-shelf welding system was capable of joining ultra-thin <200 mm wall thickness of 316L stainless steel micro-tubes, the first chosen ATLAS ITk prototype tubing material, and later CP2 Ti micro-tube of 125 mm wall thickness.

Forming a collaboration, the University of Sheffield and VBC Instrument Engineering Limited (VBCie) worked in partnership furthering the development of a unique gas tungsten arc welding (GATW) power source, the "InterPulse HMS" system. Publicity from this new welding system power supply, utilized by the aerospace and power generation industries was brought to the attention of TUoS researchers and automation was added to the InterPulse by means of an orbital weld head. The developed Constricted GATW process solved many issues from previous research papers such as numerous failures observed in space-vehicle propulsion-fuel systems due to failed welds [5, 6] and subsystem electronic component damage [7–12] induced from stray electrical arcs.

In order to maintain a global competitive advantage in the UK manufacturing sector, the UK Government identified the need for rapid development of the next generation of advanced high-value 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 by offering raw material reduction, minimizing production downtime and repair costs. Cost of repair is generally the less important factor when considering repair, time to repair is the most important consideration.

The Manufacturing, Repair and Overhaul (MRO) industry relies on significant use of manual welding with existing repair techniques. Current remanufacturing of aerospace turbine compressor blades is carried out on 80% of all recovered blades from a serviced aero engine. Human errors observed in manual welding processes to repair turbofan compressor blades largely attributes to a poor repair yield of only 45%. The robotic re-manufacturing system for high-value aerospace manufacturing is designed to recover a 100% yield of recovered blades. Extending blade life represents large savings to both aerospace engine manufacturers and airline operational costs due to repairs worth from £250 to £7 k per blade dependent on size and material.

Successful TIG welding requires highly skilled engineers who rely on experience when facing welding problems. This practice often results in human error, repetitive strain injury and loss of production control. Implementation of robotics avoids errors, reducing risk to engineers. Furthermore, automated welding solutions reduce dependencies on highly skilled personnel allowing manufacturers to invest in research and innovation.

The following text will present and describe key components of a robotic welding systems for development of a high-value aerospace manufacturing system, Sect. 2 describes industry-academia collaboration between The University of Sheffield and

VBCie, Sect. 3 discusses the system development timeline, Sect. 4 discuss the profiling of an aerospace turbofan compressor blade, Sect. 5 describes the development of high-speed data acquisition system for TIG welding, Sect. 6 highlights the development of a machine vision system for real-time welding inspection, Sect. 7 demonstrates simulations of a six axis robotic manipulator used for welding turbine blades.

2 The Industry-Academia Collaboration

Collaborative industrial research and development supported by Research Agency funding has allowed for TUoS research group expansion and established significant expertise in low heat input fusion welding, real time defect inspection and intelligent robotic systems. In-turn this has allowed successful knowledge transfer back to industry and the continued buildup of expertise.

VBCie, the industrial partner has been able to gain a depth of research knowledge and the ability to conduct blue skies research projects that would otherwise be unobtainable, ultimately using research outputs for product development. The global MRO market is currently valued at £63bn, these projects have strengthened industrial relations with aerospace and the nuclear industry [13], see Fig. 1.

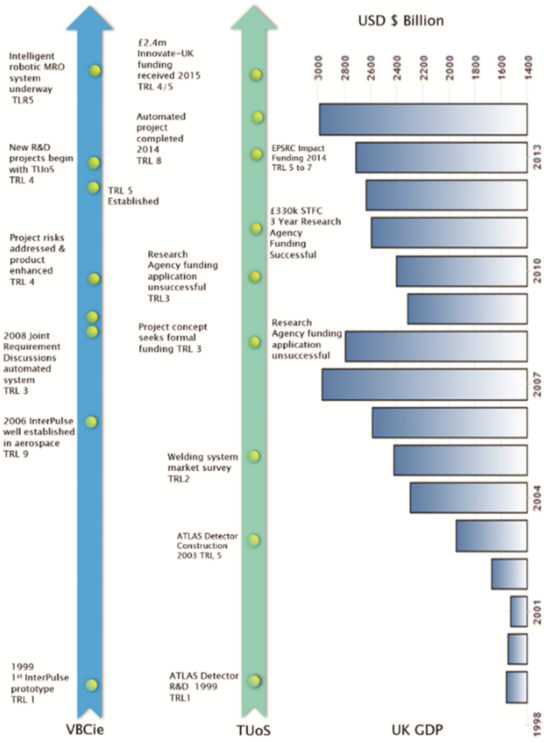

Fig. 1. Industry-academia collaboration with UK economic GDP

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 a general increase 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 research programs 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.

Current joint TUoS, VBCie & ARTC post graduate studentships now address novel challenges for the remanufacturing of both large scale (aerospace) and small-scale (ATLAS/CERN) automated low-heat welding systems. These are required for both Particle Physics detectors, nuclear and aerospace applications to work with newly developed lightweight, high strength materials.

This research project has never proceeded in a straight line. Developing new partnerships with robotics companies, vision system manufactures, 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.

3 System Development Timeline

Variable parameter changes: current, length, angle, manipulation and speed, termed CLAMS are detailed in welding procedure schedules used to provide numerical input for the manual operator to achieve correct results with high yield. Knowledgeable and experienced welding engineers apply their skills almost automatically by subtly fine-tuning multiple welding control parameters dynamically achieve the required results. These dynamic inputs modify the weld deposition characteristics such as; micro-structure, depth, size, and shape.

Effective dynamic weld correction requires intelligence, which has proven exceptionally challenging to develop when welding complex profiles and super alloy materials with minimal heat input and distortion. Widespread use by aerospace engine manufacturers of GTAW technology partially provides a solution [5, 7]. Continuous iterations of variable parameter data enable production of the correct weld deposition with high repeatability but with the inability to respond to a change in dynamics or conditions.

Development of this advanced, intelligent robotic welding system requires the correct relationship between welding parameters and corresponding outputs. Advanced programming of robots, data interpretation from integrated sensory and feedback systems are required to replace a human welder's expertise. Intelligence within the control loop can only be accomplished by key technologies such as electronic sensors, machine vision systems, high-speed data acquisition and control systems.

Timely development of disruptive intelligent robotic technologies for remanufacturing is non-trivial. The cyclic nature of global 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. The relationship and project development timeline [14–18] is shown in Fig. 2, beginning with requirements for an alternative to joining ultra-thin tubes for the next LHC upgrade to the development of intelligent robotic remanufacturing solutions for aerospace and nuclear sectors.

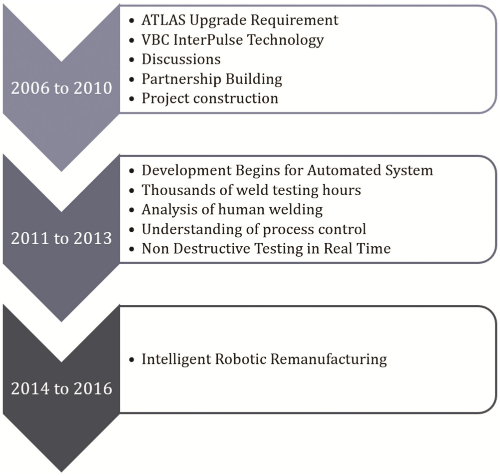

Fig. 2. Project development timeline

In 2006, the technology was simply not available even though the requirements were known. Considerable amounts of research analyzing the specifications of commercial off-the-shelf technologies was conducted. Fortunately, a theoretical solution was proposed by the academy-industry collaboration between TUoS [19, 20] and the VBCie [21] who provided the know-how and technology respectively. The following four years refined concepts as technology matured and by 2010, research funding concepts were made. Construction of the initial demonstrator was funded by the STFC Innovations and Partnerships Scheme in 2011. 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. Realization quickly matured, easily applying the technique for orbital welding of stainless steels to titanium alloys. This revolutionized the approach of the project and allowed entry into the aerospace domain for the collaboration.

High value aerospace gas turbine blades are subjected to extreme temperatures during operation, every 30000 h of airtime, engines are entirely overhauled, and worn blades are taken out for repairing and refinishing using manual weld deposition. Only half of all blades are reclaimable, although current yield is only around 80% of that half due to high heat input during welding and poor practice.

The aerospace industry deals with Maintenance, Repair and Overhaul (MRO) in relation to the blade repair systems for aerospace turbofan engine. In 2014, VBCie in partnership with Sheffield University were awarded significant funding from Innovate-UK and the Aerospace Technology Institute (ATi) to design and develop a robotic aero turbine blade re-manufacturing system [22].

The objective of this industry-academia research project is to identify both wear on the blade and carry out a low heat input weld build up and potentially doubling its existing service life. This automated solution will gather wear data using profile detection and machine vision prior repairing the blade. Real-time welding data will be evaluated using a NDT (non-destructive testing) high-speed data acquisition system [23, 24]. VBCie's InterPulse technology is ideally suited to any application that benefits from low heat input temperature. This data can be fed back to the blade manufacturer to further both service life, design and efficiency to increase throughput and save on scrapping blades.

Intelligent systems for the autonomous re-manufacturing robot are constructed in modules to mirror human cognition and dynamic response. The inspection module dictates the automatic loading and unloading of blades, automatic part recognition, selection of the weld program, weld torch with wire feed and work piece tooling. The system automatically identifies different types of blades continuously and assigns the corresponding welding data to follow (Fig. 3 shows a representative system design). In the following sections, the main unit modules will be explained. Photographic illustration of the final system cannot be shown in this publication due to commercial protection.

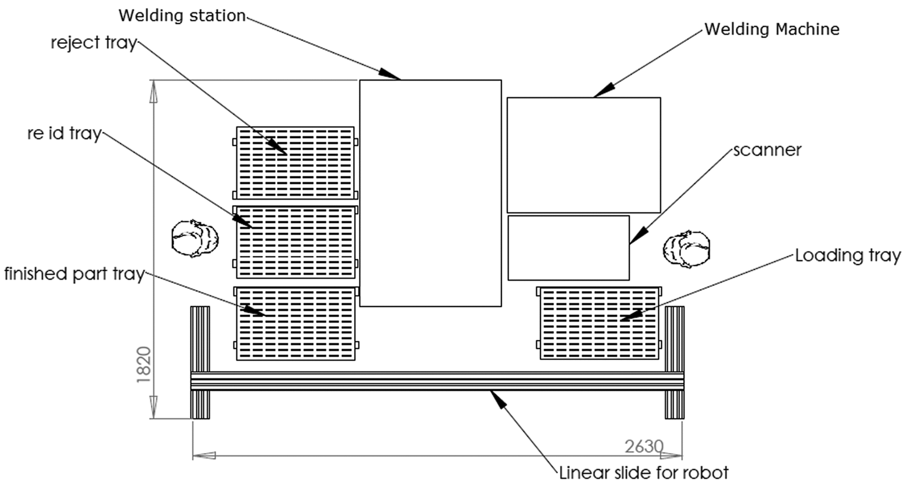

Fig. 3. Graphical representation of modular elements of turbofan re-manufacturing system

4 Aerospace Turbofan Compressor Blade Profiling

Profile detection is used in the image analysis of turbofan compressor blades to locate the blade edges with high accuracy. Edge detection is an effective tool for many machine vision applications and it provides information about the location of the boundaries of objects and the presence of discontinuities, see Fig. 4.

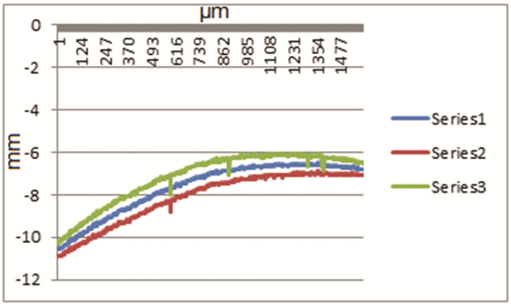

Fig. 4. High-speed blade-profile detection: upper (green), lower (red) and centre (blue) (Color figure online)

Detection helps to determine if a defect is present using line profiles and edge detection. When performing measurements to determine if a blade under inspection is manufactured correctly, the part is either accepted or rejected, depending on whether the main parameters fall inside or outside of the manufacturer tolerance limits. An edge along the line profile is defined by a technique that levels the contrast between background and foreground and the slope of the transition. The position and orientation of the blade can be determined from the profile detection data then used by the tracking control system of the robotic manipulator, see Sect. 6.

5 High-Speed Data Acquisition System

VBCie and the University of Sheffield have developed a novel low-current and automatic GTAW orbital welding system called the Heat Management System (IP50-HMS). The IP50-HMS produces accurate narrow bead welds and offers excellent weld quality and control over the weld process of high quality materials such as titanium and steel super alloys. 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 autogenous butt welded 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 [23].

The STFC funded an Innovations Partnership Scheme (IPS) project with VBCie & TUoS. The objective was to transfer technology and expertise, developed using STFC research, to the marketplace in partnership with industry. Electrical measurements of arc voltage, current and input power measurements of the VBCie system were obtained using a novel high-speed DAQ system previously developed by the University of

Sheffield to determine system accuracy. The portable signal-conditioning device can be used to measure DC and AC welding current and voltage signals and therefore can be used to evaluate GTAW welding systems. Electrical measurements are obtained and analyzed to determine if a weld deposition has been successful or not in real-time, see Fig. 5. Detailed observations have shown no structural or geometrical imperfections in the weld bead monitored using the developed DAQ. Micro-hardness tests have also been performed according to standard BS EN 1043-2:1997 [25] and all of the welds have successfully passed in accordance with the standard.

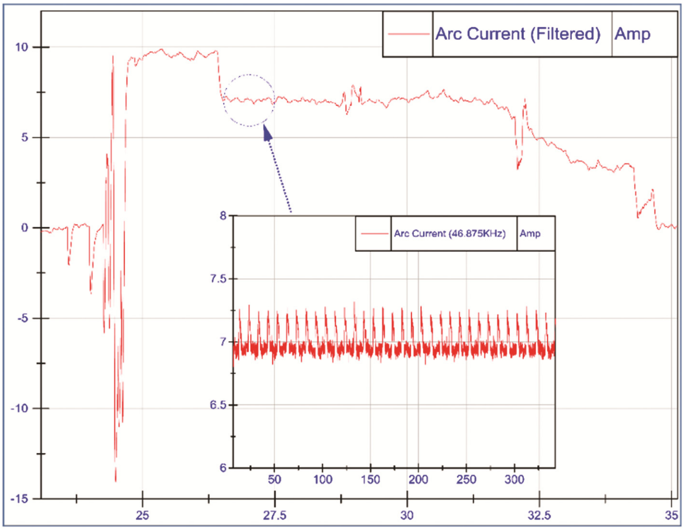

Fig. 5. High-speed current measurement of a successful weld deposition. Inset figure shows a weld region with uniform penetration

6 Machine Vision for Welding Robots

The primary aim of the machine vision system will be to detect the incoming parts and interface to the welding system to ensure it is at the correct position and orientation. 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. The vision system will be able to detect cracks and shape deformation on turbofan compressor blades to provide a NDT method of blade testing. This high-resolution stereo camera bar system can also be integrated with the robotic re-manufacturing system for tracking control.

One key aspect to achieve welding process automation is the visualization of the weld. A 3D stereo vision system was used to image the welding process for monitoring and inspection purposes [26]. A camera and lens combination, chosen in order to achieve a resolution 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 MP camera with a 1/3 in 3.75 μm pixel pitch global shutter CMOS sensor and a macro lens with a variable focus from 13–130 mm were 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.

The vision system 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. This technology has great potential to be developed not only for robotic welding systems but also for other automated systems that require vision systems.

Figure 6 shows a snapshot of TIG welding during the first stage testing of the vision system. 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.

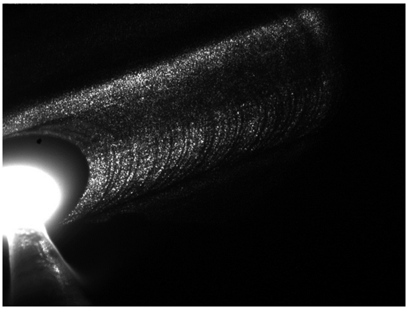

Fig. 6. Snapshot image of the TIG welding tip, pool and bead

A second camera is used to acquire the welding process simultaneously from two separate angles. The images are then 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 used by the welding robot for controlling the welding process by adjusting parameters such as voltage intensity, distance between the arc tip and sample and welding speed.

7 Simulation of Welding Robot Kinematics

Kinematic robot simulation of the robot manipulator and the interaction with key components of the robotic re-manufacturing system (welding machine, vision system, blade tray, etc.) are performed using V-REP and ROS-Industrial. The robot simulator V-REP is based on a distributed control architecture: each model can be individually controlled via a ROS node or a remote API client. All these make V-REP ideal for simulating algorithms to control the six-axis robot manipulator. V-REP's motion planning module allows handling motion-planning tasks to allow computing a welding trajectory from a start configuration to a goal configuration in S-shape, 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 the position and orientation in Cartesian space of the end-effector.

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

An open-source project that extends the advanced capabilities of the ROS software to manufacturing is ROS-Industrial. The benefits of ROS-Industrial include, custom inverse kinematics for manipulators, including solutions for manipulators with six degrees-of-freedom such as the robotic manipulator. 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 reduces costs. This property is useful in low-volume applications or with slight variations in work pieces, such having different types of blades on the same batch or tray.

An example of the ROS Industrial program when inclusive with modern robotic software generally contains packages that provide nodes for communication with the robot controller, degree of freedom models for the six axis robot arm and associated arm navigation and motion control packages [27], see Fig. 7.

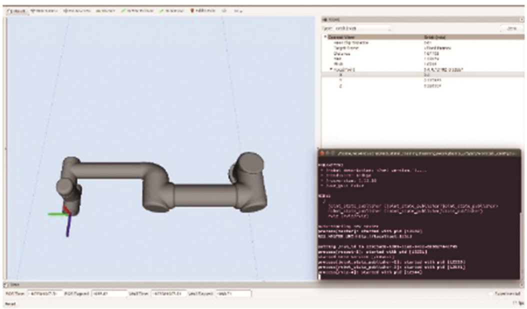

Fig. 7. ROS 6-axis robot arm simulation in a workcell MoveIt environment

8 Conclusions

The challenges of developing a robotic re-manufacturing system for high-value aerospace manufacturing within intelligence and dynamic control are successfully addressed when each key system element is developed in-conjunction with experts in each field (Vison, Robotics and Welding). Industry-Academia collaborative research projects are challenging as they carry a high risk of failure, however, researchers in academia can aid industrial development jointly mitigating risk using simulation and high fidelity measurements. The knowledge exchange and technology developed since 2006 within this specific partnership has continued to expand into new areas. The collaboration has widened to join with other manufacturing companies, working in partnership to develop high tech, disruptive technologies for flexible manufacturing. The final functional robotic re-manufacturing system will be delivered by 2018.

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