Institution: University of Bath		
Unit of Assessment: B12 Engineering		
Title of case study: Creating next generation actuation components using additive manufacturing		
Period when the underpinning research was undertaken: 2008 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Andrew Plummer	Professor	August 2006 – present
Chris Bowen	Professor, previously Reader	August 1998 – present
Vimal Dhokia	Reader, previously Lecturer, Research Fellow, KT Fellow, Research Associate	December 2006 - present
Linda Newnes	Professor, previously Reader, Senior Lecturer	September 1991 - present
Pejman Iravani	Senior Lecturer, previously Lecturer, RCUK Academic Fellow	October 2006 - present
Stephen Newman	Professor	January 2006 – present
Alborz Shokrani Chaharsooghi	Lecturer, previously Research Associate	October 2013 - present
Period when the claimed impact occurred: 2015 - 2 November 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Research conducted at the University of Bath has had direct impact on the products and processes of Bath collaborators Moog (a global controls company with a turnover of GBP2,000,000,000), Renishaw (a GBP600,000,000 global metrology and manufacturing company) and Blatchford (the UK's leading lower limb prosthetics company and 3rd largest by global market share, with a turnover of GBP90,000,000).

The University of Bath has researched specific aspects of additive manufacture (AM) using Selective Laser Melting, including design constraints, material properties, fatigue performance and strategies for post processing, with a particular focus on hydraulic actuation components. As a result of Bath research, Moog AM products have now reached the marketplace, starting with an integrated robot actuator in 2017. The research has underpinned a new strategy in Moog, with GBP30,000,000 investment in AM and associated post-processing capabilities. This includes the formation of two dedicated AM centres for development and manufacturing, 48 jobs, and the purchase of the 120-person company Linear Mold. Renishaw estimates an additional GBP10,000,000 - GDP15,000,000 of revenue generated annually through sales of Selective Laser Melting machines directly linked to the collaborative research undertaken at the University of Bath, and an additional 20 engineering jobs. In Blatchford, the research has supported the development of a range of new robotic prosthetics products, leading to a radical change in the company's technology development strategy to focus on highly optimised and integrated additively manufactured devices.

2. Underpinning research

Additive manufacturing has enormous potential for changing the way in which both traditional and new products are realised. However, there are significant challenges: New AM design methods are needed; material properties, microstructure, and fatigue performance of built parts must be understood; and strategies for post processing must be developed, i.e. integrating AM with subtractive finishing operations such as milling and drilling. Bath's research contribution to this revolution encompasses all these areas. A key motivation was working with industrial collaborator Moog to improve safety-critical aerospace actuation components, for example reducing weight, stress-concentrations and part count. Moog Inc is a major global designer and manufacturer of high-performance motion and fluid control systems for aerospace, defence, industrial and medical applications, with a turnover of GBP2,000,000,000. For example, it is by far the world's largest manufacturer of precision hydraulic control valves (servovalves) for aircraft actuation systems, and this field is also a research strength of the University's Centre for Power Transmission and Motion Control. A Moog-funded research project from 2008-11 (led by Plummer) investigated fundamental new servovalve concepts, and a KTP with Moog (2009-11, PI Newnes) focused on manufacturing improvement, and introduced AM as an industrially-relevant process to the company [A]. These led to the IUK 'VITAL' project (Valve Integration Through Additive Layer manufacturing, 2012-15, PI Plummer). This introduced long-time Bath collaborator Renishaw to Moog to work with Bath on new valve actuation, sensing and manufacturing, particularly focused on powder-bed fusion additive layer manufacturing (also known as Selective Laser Melting, SLM). As a developer and manufacturer of SLM machines, this helped inform Renishaw to improve machine design and control. Bath-Moog-Renishaw collaborative research continued in the IUK 'FALCON' project (Finishing of Additive Layer Components on a Novel Platform, 2015-18, PI Dhokia) to tackle the key issue of integrating subtractive finishing operations for additively manufactured parts. Research into new valve concepts exploiting the design freedoms of SLM also continued in an industrially-funded project (2015-17) and via an EU Marie-Curie Fellow (2017-19), both supervised by Plummer. As Moog states: "*VITAL and subsequent Bath research allowed Moog, in association with Renishaw, to acquire novel AM research insights, leading to the development of a strategic relationship with Renishaw, and to the creation of a Moog AM technology centre, with investment of GBP2,000,000 in the first year (2015).*" [A].

Fig 1. AM servovalve resulting from the VITAL research project – giving 40% weight reduction amongst many other benefits

Bath SLM materials-related research investigated the correlation of microstructure and fatigue performance with manufacturing process parameters, focusing on titanium alloy Ti-6AL-4V [1]. The research found that with appropriate process parameters and heat treatment, a substantial weight saving could be achieved while maintaining acceptable fatigue life for complex high-pressure hydraulic actuation components such as servovalves [2]. Other benefits that were confirmed are less material waste, freedom for flow gallery routing without the need for 'line of sight' for machining, fewer parts and fewer hydraulic interfaces (reducing the number of seals, screws and plugs), reduced dead oil volumes and elbow pressure losses, and potential for geometry optimization to reduce stress concentrations. The short design/prototyping cycle time is also a major benefit, reducing development time. Specific research on etching to reduce internal surface roughness was also undertaken.

Manufacturing research focused on post-processing (machining) requirements and development of a new manufacturing process chain encompassing design, AM, machining and inspection [3]. The AM parts considered in our research all require post-processing using subtractive machining to provide a sufficiently good surface finish to mate to other parts [4]. This post-processing causes a significant manufacturing bottleneck solved by hybrid manufacturing methods which properly integrate the additive and subtractive operations as developed at Bath [3, 5].

Latterly research has also included the application of the developed AM methods to new devices, in particular using the design freedom provided to better integrate complex structural, actuation and control systems. An example is the development of smart powered prosthetics from lab prototypes to commercial products [6], in association with Blatchford Ltd. Blatchford's Technical Director states: "*Bath developed and investigated a proof-of-principle powered hydraulic ankle. … At the time, parallel work at Bath in collaboration with Moog was researching the design and manufacture of hydraulic components using additive methods. This gave an ideal opportunity for achieving the size and weight reductions required for the ankle. Following the introduction by Bath, Blatchford entered a partnership with Moog, who would develop, manufacture and supply AM-based actuation components based on the Bath research"* [C].

3. References to the research

[1] Tong, J, Bowen, C & Plummer, A. 2017. 'Mechanical properties of titanium-based Ti–6Al–4V alloys manufactured by powder bed additive manufacture', *Materials Science and Technology*, vol. 33, no. 2, pp. 138-148. https://doi.org/10.1080/02670836.2016.1172787

[2] Persson, L, Plummer, A, Bowen, C & Brooks, I. 2016. 'A lightweight, low leakage piezoelectric servovalve. in Proc Recent Advances in Aerospace Actuation Systems and Components' 2016. Recent Advances in Aerospace Actuation Systems and Components 2016, Toulouse, France, 16/03/16. [Available on request]

[3] Kendrick, BA, Dhokia, V & Newman, ST. 2017. 'Strategies to realize decentralized manufacture through hybrid manufacturing platforms', *Robotics and Computer-Integrated Manufacturing*, vol. 43, pp. 68-78. https://doi.org/10.1016/j.rcim.2015.11.007

[4] Zhu, Z, Dhokia, V, Nassehi, A & Newman, ST. 2016. 'Investigation of part distortions as a result of hybrid manufacturing', *Robotics and Computer-Integrated Manufacturing*, vol. 37, 1348, pp. 23-32. https://doi.org/10.1016/j.rcim.2015.06.001

[5] Newman, ST, Zhu, Z, Dhokia, V & Shokrani, A. 2015. 'Process planning for additive and subtractive manufacturing technologies', *CIRP Annals - Manufacturing Technology*, vol. 64, no. 1, pp. 467-470. https://doi.org/10.1016/j.cirp.2015.04.109

[6] Yu, T, Plummer, A, Iravani, P, Bhatti, J, Zahedi, S & Moser, D. 2019. 'The design, control and testing of an integrated electrohydrostatic powered ankle prosthesis', *IEEE/ASME Transactions on Mechatronics*, vol. 24, no. 3, pp. 1011-1022. https://doi.org/10.1109/TMECH.2019.2911685

4. Details of the impact

The research has underpinned a new strategy in **Moog**, with considerable investment in AM capability (currently GBP30,000,000) [A]. This includes development of an Additive Technology Centre (ATC, for R&D) and an Additive Manufacturing Centre (AMC, for production), and the purchase of the 120-person ALM company Linear Mold for USD11,000,000 in 2015 [A, E] The ATC is led by the Bath researcher who was pivotal in the original VITAL project. Moog benefitted from Renishaw developing its AM process based on

the Bath research collaboration, and consequently Moog invested in Renishaw AM machines for the ATC and AMC. Renishaw has also invested in a new additive manufacturing laboratory at the University of Bath to carry on research in this area. Moog's Principal Engineer states [A]:

> "*Moog's current development strategy heavily leverages AM technologies researched at Bath… AM powered technologies are starting to drive substantial growth in the Moog business, enabling traditional Moog expertise to be applied in new markets, such as robotics*".

Building on Bath research, Moog additively-manufactured AM products have now reached the marketplace, starting with an integrated robot actuator in 2017, which reached GBP180,000 of orders by the start of 2020 [A, E, F]. Several aerospace actuation products have now been developed [D]. One that has entered production is a Locking Collar for Embraer S.A. Moog states [I]:

> "*For aerospace applications, AM provides significant opportunities for weight savings. We have seen the ability to reduce weight between 10-50%, which is a great value to our customers in their applications. We are also seeing the potential for AM to provide faster development cycles*".

A new application for Moog AM actuation is powered prosthetics. Lower limb prosthetics manufacturer **Blatchford** has been supporting research into smart powered prosthetics at Bath since 2013. Blatchford is amongst the three leading companies in the field worldwide. At Bath's instigation, Moog entered a strategic partnership with Blatchford to develop prosthetic actuation systems based on Moog's new AM capability. An IUK project between the 3 parties, ACTIPh (Additive Constructed Transtibial Intelligent ProstHetic, 2017-19) has developed a new AM ankle (pictured), currently undergoing clinical trials. A new AM knee-ankle orthosis product has also been developed based on the same principles aimed at polio patients. Bath's impact is a change in practice within Blatchford. As the company states [C]:

Fig 2. A new AM ankle

> "…*the research undertaken at Bath, and exploited by Moog, has now enabled us to radically change our technology development strategy to focus on highly optimised and integrated additively manufactured devices. These are not only benefitting the Company but will also help many amputees the world-over to have a better quality of life*".

Moog currently has in place plans for a 35% growth in the Moog Industrial group facility in the UK in order to support manufacture of the new Blatchford product line [A].

At **Renishaw**, Bath research has enabled a new AM machine to reach the marketplace. According to Renishaw's Director of Group Technology [B]:

> "*As a result of the work in VITAL Renishaw was able to gain a detailed understanding of the limitations of its then current SLM platform in terms of meeting part quality standards for aerospace applications which then led directly to design work to effect significant capability improvements in its recently introduced 500ML platform, which is now world leading in terms of material properties and part quality for aerospace applications. This has led to a major uplift in sales for this new platform. It is estimated that there has been*

an additional GBP10,000,000 - GBP15,000,000 of revenue generated annually directly linked to the collaborative research undertaken at Bath on VITAL".

Further, the Bath research as part of the FALCON project into design for AM manufacture enabled Renishaw to [B]:

"…*understand in detail the requirements for process finishing of metal additively built parts and an holistic approach to 'Design for Manufacture' for the entire AM process chain from powder to finished part …This has led to an additional 20 engineering roles having been created to support sales for Renishaw AM technology which can be traced back to the collaborative research undertaken at Bath on FALCON".*

Linked to the GBP30,000,000 investment, Moog jobs created or safeguarded as a result of the Bath research are 18 in the UK and 30 in the US by early 2020 [A]. Revenue growth attributable to AM at Moog's UK Tewkesbury site is estimated at 5% currently [A]. Moog states that [A]:

"…*work with Bath since 2009 has positioned us as a leader in this industrially relevant technology, that has resulted in several growth vectors that are starting to have a significant effect on the financial results of the corporation, as well as radically changing Moog's strategy and processes. This has already created high value jobs in the UK and the US, and will continue to do so as Moog convert this new technology into industrially relevant products in new and existing markets. Moog credits the University of Bath with providing the critical knowledge, research results and inspiration at key moments*".

5. Sources to corroborate the impact

[A] Testimonial letter from Principal Engineer, Moog, 5 February 2020.

[B] Testimonial letter from Director of Group Technology, Renishaw, 2 November 2020.

[C] Testimonial letter from Technical Director, Blatchford, 19 December 2019.

[D] Moog paper on AM product development: Guerrier, P, Zazynski, T, Gilson, E, and Bowen, C. 2016. 'Additive manufacturing for next generation actuation'. Paper presented by Moog at Recent Advances in Aerospace Actuation Systems and Components, Toulouse, France, 16 March 2016 (first 3 are Moog authors).

[E] Moog. 2017. Integrated Smart Actuator product brochure. Available at: https://www.moog.com/content/dam/moog/literature/ICD/Moog-Microhydraulics-Integrated-Smart-Actuator-Datsheet-en.pdf

[F] Moog. 2017. When performance really matters. Annual report, p.10.

[G] Small, G. 2013-2018. 'A new way of looking at Metal Additive Manufacturing Processes', Moog. Available at: https://www.moog.com/news/blog-new/Innovation/GeorgeSmallVeripart_1.html

[H] Moog. Annual report pursuant to section 13 or 15(d) of the Securities Exchange Act of 1934. For the fiscal year ended September 29, 2018 (particularly page 30).

[I] Gannon, M. 2019. 'Talking additive manufacturing and hydraulics with Moog'. *Fluid Power* World. 17 September. Available at: https://www.fluidpowerworld.com/talking-additive-manufacturing-and-hydraulics-with-moog/