Institution: University of Sheffield		
Unit of Assessment: B-12 Engineering		
Title of case study: Automating BAE Systems defence aircraft manufacture		
Period when the underpinning research was undertaken: 2008–2018		
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:**
Ozturk, E.	Senior Technical Fellow	2010–present
Sharman A.	Head of NAMTEC	2003–present
Kerrigan, K.	Group Head of Composite Machining	2013–present
Wika, K.	Technical Fellow	2012–present
Ridgway, K.	Professor of Design and Manufacture	1988–2019
McLeay, T.	Head of Research, The Machining Group	2008–2016
Harris, K.	Post-Doctoral Researcher	2013–2016
Dodd, T. J.	Professor of Autonomous Systems Engineering	2002–2019
Period when the claimed impact occurred: 2015–2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

The University of Sheffield's research into composite machining, automation, and non-contact metrology has pioneered a novel, fully automated manufacturing process. Operational at BAE Systems Samlesbury facility since 2015, Sheffield's process has been used to produce critical fuselage panels for over 500 F-35 Lightning II aircraft, realising over £15m in cost savings and directly supporting hundreds of advanced manufacturing jobs in the UK. Sheffield was recognised in 2018 with a BAE Systems Chairman's Award. Wider impact includes augmenting expertise, providing new technology and capabilities within the aerospace industry, and supporting the manufacture, sustainment, and uptake of the world's largest defence programme.

2. Underpinning research (indicative maximum 500 words)

Through their ongoing research collaboration, BAE Systems approached the University of Sheffield's Advanced Manufacturing Research Centre in 2012 for help operationalising their concept for an alternative and cost-effective, method to replace manual countersinking of thousands of pre-drilled fastener holes in the composite panels used on the F-35 Lightning II stealth aircraft.

Industrial robotic systems are typically used in applications, such as car assembly, for which the acceptable positional accuracy is an order of magnitude less than that required for military stealth aircraft applications. Applying the University of Sheffield's research knowledge in the fields of composite machining, automation, and non-contact metrology to the challenge presented by BAE Systems enabled the development of a pioneering flexible robotic countersinking technology capable of meeting the exacting tolerances required for military aerospace components, flexibly handling variations in highly geometrically complex panels, shortening cycle rates, and enabling 24-7 operation.

The first step in the process requires the robot to robustly position the countersinking tool ensuring it is both concentric and normal to the pre-drilled hole on a double curvature surface. Based on Sheffield's research into data fusion, a metrology/inspection algorithm was developed from multiple-source data to correct any inaccuracies in the robot's position with respect to the pre-drilled hole **[R1]**. The resulting metrology/inspection algorithm was able to obtain data from a number of sources and correct the robot's position relative to the pre-drilled hole in the composite panel.

Once the robot was positioned correctly relative to the workpiece, the accuracy and quality of the countersink were largely determined by the combination of the static and dynamic stiffness of the robotic system, the cutting parameters, and the geometry of the cutting tool.

Industrial robots tend to be dynamically and statically flexible due to their multiple Degrees Of Freedoms. Sheffield's research showed that dimensional errors were minimised and surface quality was improved when a second robot was used to provide dynamic support during machining activities **[R2]**. The second slave robot was employed to eliminate expensive fixturing, and to improve the system's static and dynamic response while the first (master) robot undertook the countersinking operation.

The quality of the countersinking operation is strongly linked to the selection and design of the cutting tool and the tool's condition at any point in time.

Sheffield's research into real time tool condition monitoring using indirect sensor data such as acoustic emission, spindle power, and vibration of the tool led to the development of a model using naive Bayes classifiers that summarised the state of the tool after each cut **[R3, R4]**. This model was essential to determine when to change the cutting tool and so optimise productivity and achieve full automation.

Additionally, Sheffield's development of a non-contact optical technique to characterise the surface roughness of the carbon fibre panels and damage caused by machining operations has enabled an understanding of the effect of tool choice on surface quality **[R5]**. Sheffield also determined the relationship between the characteristics of tool geometry and tool performance, which has provided insights on the optimal tool geometries required for this application **[R6]**.

3. References to the research (indicative maximum of six references)

University of Sheffield staff and students given in **bold**

R1. **Martinez-Hernandez, U., Dodd, T. J.**, Evans, M. H., **Prescott, T. J.**, & Lepora, N. F. (2017). Active sensorimotor control for tactile exploration. *Robotics and Autonomous Systems*, *87*, 15–27. https://doi.org/10.1016/j.robot.2016.09.014. Cited by 28.

R2. **Ozturk, E.**, Barrios, A., **Sun, C., Rajabi, S.**, & Munoa, J. (2018). Robotic assisted milling for increased productivity. *CIRP Annals*, *67*(1), 427–430. https://doi.org/10.1016/j.cirp.2018.04.031. Cited by 9.

R3. **Harris, K., Triantafyllopoulos, K., Stillman, E.**, & **McLeay, T.** (2016). A Multivariate Control Chart for Autocorrelated Tool Wear Processes. *Quality and Reliability Engineering International*, *32*(6), 2093–2106. https://doi.org/10.1002/qre.2032. Cited by 7.

R4. Karandikar, J., **McLeay, T., Turner, S.**, & Schmitz, T. (2014). Tool wear monitoring using naïve Bayes classifiers. *The International Journal of Advanced Manufacturing Technology*, *77*(9–12), 1613–1626. https://doi.org/10.1007/s00170-014-6560-6. Cited by 34.

R5. **Duboust, N., Ghadbeigi, H., Pinna, C., Ayvar-Soberanis, S.**, Collis, A., **Scaife, R.**, & **Kerrigan, K.** (2016). An optical method for measuring surface roughness of machined carbon fibre-reinforced plastic composites. *Journal of Composite Materials*, *51*(3), 289–302. https://doi.org/10.1177/0021998316644849. Cited by 20.

R6. **Wika, K. K., Sharman, A. R. C.,** Goulbourne, D., & **Ridgway, K.** (2011). Impact of Number of Flutes and Helix Angle on Tool Performance and Hole Quality in Drilling Composite/Titanium Stacks. *SAE Technical Paper Series*, 2011-01–2744. https://doi.org/10.4271/2011-01-2744. Cited by 8.

4. Details of the impact (indicative maximum 750 words)

The F-35 Lightning II, produced by Lockheed Martin, is a result of a multinational collaboration between the USA, UK, Italy, the Netherlands, Australia, Norway, Denmark, and Canada focussing on the delivery of a multi-functioning, stealth attack aircraft **[S1]**. To stimulate and sustain the sale of F-35 aircraft, the US Department of Defense announced the "Blueprint for Affordability", which committed to lowering the cost of the F-35 to under $85m per aircraft by 2019 **[S2 p.27]**. This cost reduction target posed a major production challenge within the aerospace manufacturing industry.

BAE Systems is the largest defence contractor in Europe, and as the only level 1 partner on the F-35 programme, has a 13-15% manufacturing workshare for each F-35 aircraft, which includes the supply of the aft fuselage **[S3]**. Driven by the need to reduce manufacturing costs, whilst at the same time increasing production volumes, BAE Systems sought to revolutionise their manual process for countersinking holes (over 25,000) in over 50 carbon fibre parts [text removed for publication] **[S4 p2]**. Through the application of the outputs of a number of Sheffield's research streams, a pioneering flexible, robotic, countersinking technology capable of 24-7 operation was developed. The technology was able to countersink holes to less than 1mm tolerance [text removed for publication] **[S4 p5]**. The robotic cell was deployed into production at BAE Systems' Samlesbury facility in June 2015 and has subsequently delivered cost savings of [text removed for publication] **[S4, S5]**.

The Technology Delivery Director at BAE Systems stated that *"research conducted at the University of Sheffield was instrumental in deciding the equipment, tooling and cutting parameters that we used to scale up production rates for the F-35"* he continued, *"The new approach has had a major impact on part quality and reduced concessions associated with the original process."* **[S5].** This has directly enabled BAE to deliver components for over 500 aircraft in the last 5 years **[S1, S5]**.

He summarises, *"The University of Sheffield's research was critical to BAE Systems and played a significant part in helping the company meet its F-35 programme affordability commitments."* **[S5]**.

The resulting socio-economic impact is outlined below:

Economic impact

The flexible robotic countersinking technology developed by the University of Sheffield has delivered capital and operational cost reductions for BAE Systems.

- The upfront capital equipment cost was saving was over £5m [text removed for publication].
- The improved utilisation of floor space and rationalisation of the number of machines required to meet production targets has relieved the need for larger premises **[S5]**. [text removed for publication]
- The fully autonomous manufacturing approach saved person-hour and cutting tool costs totalling £10m between [text removed for publication] **[S4 p3, S5]**.

The reputation and role of BAE Systems, as a global giant in the supply of F-35 military aircraft to the international market, has been bolstered as a consequence of Sheffield's research. The new cost-effective technology has strengthened corporate capabilities and competitiveness within the aerospace manufacturing market.

The Technology Delivery Director at BAE Systems stated, *"the University of Sheffield's research has contributed toward securing long term manufacturing work in the UK and directly supported 100's of advanced manufacturing jobs."* **[S5]**. Oxford Economics reported that for BAE Systems military aircraft business in 2016, 70% of its 12,300 jobs were in highly skilled roles with a gross value added per full time equivalent employee being £76k, six percent higher than the UK average. BAE Systems directly contributed £900m to UK GDP with an economic multiplier of 3.4 for every 100 jobs in the organisation **[S6 p1]**. BAE Systems directly employs 1,800 people in the UK to support the F-35 programme **[S3]**, and the total gross value added is approximately £137m.

Impact on practitioners within the aerospace defence industry

Sheffield's research has developed a new production line process for F-35 aircraft, which surpasses the existing state of the art. This has unquestionably augmented knowledge within the aerospace industry, specifically in the use of robotic systems for hole countersinking and provided a critical new capability. The research, resulting technology, and improved product quality was recognised within industry by a BAE Systems Chairman's Award in 2018 **[S5]**. The Assembly & Systems Technology Lead for Manufacturing Technology at BAE Systems stated, "*This technology sets a new benchmark for BAE Systems manufacturing capability and the expertise within the Advanced Manufacturing Research Centre was core to delivering this to production*." **[S7]**.

Impact on international security policies

Ultimately, Sheffield's work has helped to lower the production costs of F-35 aircraft, adhering to the US Department of Defense's "Blueprint for Affordability". This increases the international appeal of the F-35 defence programme, presenting an affordable option to stimulate uptake from global governments and support national and international defence capabilities.

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. F-35 Lightning II Program - status and fast facts, Lockheed Martin. Reports the countries involved and number of aircraft manufactured. (Accessed 4th Dec 2020). https://www.lockheedmartin.com/content/dam/lockheed-martin/aero/documents/F-35/F-35_Lightning_II_Program_Fast_Facts_-_November_2020.pdf

S2. Congressional Research Services report RL30563 on the "F-35 Joint Strike Fighter (JSF) Program" report for the members and committees of Congress (May 2020). The Department for Defence Blueprint for Affordability - page 27 reports the 2014 unit cost projection target for each F-35 aircraft in 2019. (Accessed 7th Dec 2020). https://fas.org/sgp/crs/weapons/RL30563.pdf

S3. BAE Systems F-35 Facts webpage. Reports BAE Systems F-35 manufacturing workshare and direct employment numbers. (Accessed 18th Dec 2019). https://www.baesystems.com/en-uk/product/f-35

S4. Confidential BAE Systems Chairman's Award Presentation. Corroborates technical details & economic impact of the research collaboration.

S5. Confidential testimonial letter from the Technology Delivery Director at BAE Systems (October 2020). Corroborates a) technology deployment into production, b) cost savings, c) process improvements, d) number of aircraft delivered, e) jobs secured & f) BAE Systems Chairman's Award.

S6. The Impact of the BAE Systems Military Aircraft Business on the UK Economy report by Oxford Economics (July 2018). Page 1 reports the economic impact of BAE Systems Military Aircraft Business to the UK economy. (Accessed 4th Dec 2020). https://www.oxfordeconomics.com/recent-releases/2a840165-0dd8-4609-ad97-650c4d161876

S7. University of Sheffield press release quoting Assembly & Systems Technology Lead for Manufacturing Technology at BAE Systems (2017). Corroborates various awards and the role of Sheffield's research. (Accessed 27th Jan 2021). https://www.sheffield.ac.uk/news/nr/sheffield-amrc-award-bae-systems-1.704973