Institution: Glyndŵr University		
Unit of Assessment: UoA12 - Engineering		
Title of case study: Economic Impacts of Computer Controlled Polishing and Metrology of Ultraprecision Surfaces		
Period when the underpinning research was undertaken: January 2010 to August 2017		
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:**
Professor Paul Rees	Professor of Optics: Technology and Metrology	May 2010 – present
Professor David Walker	Professor of Optics	October 2009 – August 2016
Dr John Mitchell	Senior Metrologist	February 2012 – present
Dr Guoyu Yu	Senior Research Lecturer	December 2009 – August 2016
Dr Gareth Roberts	Software Modeller	October 2012 – April 2016
Dale Blackmore	Senior Optical Polisher	June 2014 – present
Dylan Roberts	Senior Optical Polisher	April 2019 - present
Period when the claimed impact occurred: January 2016 to December 2020		
Is this case study continued from a case study submitted in 2014? N		

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

Glyndwr University created the Precision Optical Systems Group within Glyndwr Innovations Ltd. (GIL), a wholly owned subsidiary company of the University, to deliver the high-value optical surface manufacturing capability developed at the University.

Starting in December 2015, the group has placed the UK in the supply chain for large and complex optics for the first time since the closure of Grubb Parsons in 1985. It has built a reputation for delivering highly complex optical components and systems to a number of industry-leading organisations within the science base, precision engineering and aerospace and defence sectors, including Trioptics (France), Thales (France), Leonardo (UK), Centro de Estudios de Fisica del Cosmos de Aragon (CEFCA, Spain), Green Optics (South Korea) and Oxford University (UK). It has also continued to develop new polishing and metrology methods for these sectors and benefited collaborators such as Zeeko, IDOM, BAE Systems, and DIOPTIC.

The impact is twofold:

1. An economic contribution to the collaborators of Glyndwr University
2. Technology capability development and transfer between Glyndwr University and its collaborators and beneficiaries

2. Underpinning research (indicative maximum 500 words)

The research has developed state-of-the-art high-precision surface removal processes and related metrology applied to the fabrication of large optical surfaces, producing accuracies of order <10 nm. Whilst developed in the context of the serial manufacture of Extremely Large Telescope (ELT) primary mirror segments and suitable for serial and volume manufacture, these techniques are of broader utility and enable the cost-effective fabrication of large precision optics.

The research is in response to increasing market demand for larger optical surfaces from the science base, aerospace, and defence and security sectors. Each of these sectors records increased demand for optical surfaces greater than 500 mm "diameter"; surface accuracies well below 20 nm Root Mean Squared (RMS); and forms ranging from optically flat or spherical through symmetric aspherical to off-axis and free-form. The research has developed a set of Computer Numerical Controlled (CNC) polishing and metrology methods able to commercially deliver the highest specifications required by these sectors.

Research underpinning the polishing of European ELT segments (ref 3.a, 3.b)

Research into manufacturing large off-axis aspheric mirror-segments for future extremely large telescopes began prior to 2008 and continued through the underpinning research period. We applied our earlier advances in technical understanding to the scaling from prototype to commercial volume production of large optics. This included:

a) Development of a CNC polishing process capable of polishing to the edge of an optical surface without "turning down" optical edges (crucial in segmented mirrors to maximise image contrast required by key science objectives). **Ref 3.a** is the first published report of this capability world-wide.
b) **Ref 3.b** reports the application of small tool, CNC-controlled loose-abrasive processes to the manufacture of 1.4 meter, off-axis aspheric, hexagonal mirror-segments: prototype segments for the 39 m E-ELT. The reported results represent the first time that mirror segments have been processed entirely in the hexagonal shape – a milestone in loose-abrasive processing.

Research into metrology for optical manufacturing (ref 3c, 3d)

In-situ metrology techniques for the measurement of large optics during fabrication were developed in the context of the large-scale production of ELT segments. These techniques included methods to qualify the optical test wavefront to ensure conformance. The techniques were developed for bespoke optical testing for small-volume manufacture and to meet the high accuracy demands of today's complex optical systems.

a) In an optical test, the test wavefront defines the target optical prescription and must be qualified to an accuracy consistent with the optic being tested. If this qualification is not of sufficient accuracy, fabrication of the optic becomes unviable. For complex optical test systems, it is not feasible to calibrate using conventional optical shop practices. Reflective diffractive imitator optics were designed and used to qualify the optical test wavefront (**ref 3.c**). The absolute accuracy of the calibration achieved with this method < 20 nm RMS. The wavefront accuracy without calibration was approximately 150 nm RMS. This is the first published use of diffractive imitators in an application of this kind.
b) Interferometric measurement can lead to uncertainties in the measured radius of curvature (ROC) of an optic. A deployable pentaprism profilometer, Nano-Optic-Measuring (NOM) instrument, was developed to independently measure the ROC (**ref 3.d**) of the test optic. This instrument was used in-situ within an optical production environment. Absolute measurement uncertainties of less than 1 part in 10,000 were achieved. This is the published use of a NOM instrument for in-situ measurements of large optics in a manufacturing environment, and the first of such measurements to qualify large 2-dimensional aspheric surfaces (as opposed to linear scans only).

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

The following research papers are published in a refereed journals:

a) Walker, D., Yu, G., Li, H., Messelink, W., Evans, R., Beaucamp, A. (2012), '**Edges in CNC polishing: from mirror-segments towards semiconductors, Paper 1: edges on**

processing the global surface', Optics Express, Vol. 20, Issue 18, pp. 19787-19798. doi: 10.1364/OE.20.019787

b) Walker, D., Davies, G., Fox-Leonard, T., Gray, C., Mitchell, J., Rees, P., Wu, H.Y., Volkov, A. and Yu, G. (2014), '**Advanced Abrasive Processes for Manufacturing Prototype Mirror Segments for the World's Largest Telescope**', Advanced Materials Research, Vol 1017, pp. 532-538. doi: 10.4028/www.scientific.net/AMR.1017.532

c) Paul C. T. Rees, John B. Mitchell, Andy Volkov, Jean-Michel Asfour, Frank Weidner, Alexander G. Poleshchuk, Ruslan K. Nasyrov, (2015) "**The use of diffractive imitator optics as calibration artefacts**", Proc. SPIE 9575, Optical Manufacturing and Testing XI, 957516 (27 August 2015); https://doi.org/10.1117/12.2189809

d) Thompson, S.J., Long, R., Rees, P. and Roberts, G.W., (2016) **'Reconstruction of a conic-section surface from autocollimator-based deflectometric profilometry**', Applied Optics, Vol.55, No.10, pp.2827-2836. doi: 10.1364/AO.55.002827

The following grants contributed to this work:

1. Welsh Assembly Government A4B (Academic Expertise for Business) Programme, "Confirmation of Metrology Systems for Large Optics Polishing" (ref: HE 03 IAP 1001).
2. Welsh Assembly Government A4B (Academic Expertise for Business) Programme, "Capacity and Capability Development of the National Facility for Ultra Precision Surfaces" (ref. HE 03 16 1003).

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

New Manufacturing Methods for Ultraprecision Surfaces

The incentive for this work was the anticipated rapid market growth for large aspheric optics in the science base, aerospace, and defence and security sectors. Specifically, the serial production of aspheric primary mirror segments for the next generation of astronomical telescopes required a step-change in the manufacture of precision optics to meet the required production rates (one delivered 1.4m optic in less than 3 days).

The research undertaken by Wrexham Glyndŵr University was a ground-up programme applying newly available sub-aperture CNC polishing techniques to fabricate optics that were more accurate, complex and larger than any previously produced in volume. This included the development of metrology methods suitable for these new processes. In several cases, Wrexham Glyndŵr University was the first to design and publish these polishing techniques and metrology methods.

The resulting impacts are:

- The demonstration of a research and development capability in the manufacture of optics
- A new capability for the manufacture of large optics in the UK
- Faster methods of fabrication and verification for complex ultraprecision surfaces
- An increase in capacity for the fabrication of high accuracy, large optical components in Europe
- The economic growth of the North Wales optical manufacturing cluster

Economic and Technological Outcomes

1. Zeeko Ltd – This work has continued a close working relationship with Zeeko Ltd, the manufacturer of CNC polishing machines used at Glyndŵr University. Prior to January 2016, Zeeko had a presence in the OpTIC Centre, Glyndŵr University's St Asaph campus. During the programme to fabricate ESO ELT mirror segments, the technical relationship between Glyndŵr University and Zeeko resulted in several jointly authored research papers, furthering their scientific expertise. The OpTIC Centre also served as a "reference site" for Zeeko marketing, thus exploiting the centre's reputation for the benefit of increasing custom for Zeeko. Zeeko continues to exploit its relationship with Glyndŵr University to demonstrate its technical capability, therefore generating economic growth. ***Source 5.1***.

2. IDOM, Spain – This work has enabled a partnership with IDOM (Spain) from 2017 to successfully bid for the design and manufacture of the Prefocal Station A and B systems for the E-ELT, which include metre-scale optical flats fabricated using these CNC polishing techniques. IDOM does not have the capability to offer these optics unassisted. Contracted design work began at Glyndwr University in October 2018. ***Source 5.2***.
3. Trioptics France – This work has enabled a partnership between Trioptics (France) and Glyndŵr University for the supply of large optics in Europe. Since January 2016, Trioptics has sourced commercial optical fabrication and verification contracts worth a total of €1.6M, of which approximately €350k remains within Trioptics France. This is work that Trioptics France does not have the capability to offer unassisted. ***Sources 5.3a, 5.3b, 5.3c***.
4. BAE Systems – This work has enabled a partnership with BAE Systems from 2017 to develop manufacturing processes for optical windows fabricated from specialist materials for the next generation of military aircraft. This has resulted in three polishing trials intended to inform BAE Systems' strategic technical programme. This research is expected to develop into a long-term technical relationship with BAE Systems. ***Source 5.4***.
5. DIOPTIC, Germany – This work created a relationship with DIOPTIC GmbH (Germany) in the use of diffractive optics as verification artefacts for the manufacture of modern optics. This relationship has resulted in one jointly published paper that is used by DIOPTIC in marketing its technical capabilities. Glyndwr University has an established commercial relationship with DIOPTIC, using diffractive null lenses for the fabrication of both on-axis and off-axis aspherical mirrors. This relationship is seen by DIOPTIC as important to continue to develop its technical capability in this market. ***Source 5.5***.

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

1. Testimonial from Zeeko Ltd
2. Testimonial from Astronomy Business Manager, IDOM
3. Trioptics France - Evidence of partnership between Glyndwr Innovations Ltd and Trioptics France
    a. https://www.trioptics.fr/produits/composants-et-systemes-optiques-de-precision/optiques-de-grande-dimension
    b. https://www.trioptics.fr/produits/composants-et-systemes-optiques-de-precision/optiques-de-grande-dimension/pieces-optiques-de-grande-dimension
    c. Testimonial from Trioptics Director, France
4. Testimonial from BAE Systems, Lead Technologist
5. Testimonial from DIOPTIC, Managing Director