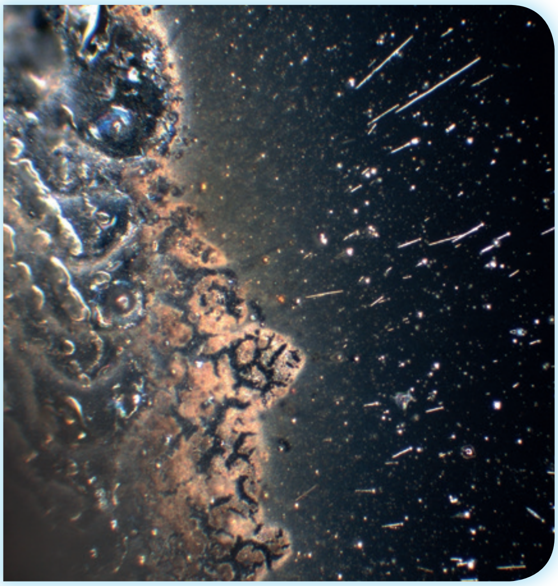
EPSRC Centre for innovative manufacturing in ultra precision

EPSRC Pioneering research and skills



Annual Report

2015

Contents

This report was prepared at Cranfield University by the EPSRC Centre for Innovative Manufacturing in Ultra Precision, led by Cranfield and Cambridge Universities. Any views expressed do not necessarily reflect those of these Universities or collaborating partners.

We would like to thank the following for assistance with images: Cranfield University, University of Cambridge, Asian Society for Precision Engineering and Nanotechnology (ASPEN) and the National Physical Laboratory.

Executive Summary

This report provides an overview of the progress made by the EPSRC Centre for Innovative Manufacturing in Ultra Precision during its 4th year. As provided in previous annual reports an overview of the complete activity is given with more detail provided for areas having intensity.

Our goal has been to better position UK companies in securing wealth creation from ultra precision manufacturing of emergent products, those demanding high accuracy for their performance but also high accuracy during arduous production processing conditions. As you will read much of our research towards developing the major research platforms has been carried out in collaboration with UK companies. These companies offer expertise and sub-systems for the Centre's ultra precision platforms and these in combination with our research staff outputs have led to truly world leading bespoke systems.

It is reassuring to see numerous UK companies contributing to the Centre's major research platforms. Creating manufacturing supply chains for next generation production lines is a fundamental endeavour of this EPSRC Centre. It remains clear the UK manufacturing supply chains for production systems has significantly been "hollowed out". Our efforts to support a repair of this issue should be evident by our partners and how we have incorporated their expertise and products to realise bespoke research systems that promise a world lead performance.

Whilst much of the research is low TRL in nature we have spanned the TRL levels with regards to designing and building the research platforms. Ultimately, their performance will be at a high TRL level as their pathway to commercialisation takes place.

The aligned Centre for Doctoral Training in Ultra Precision (CDT-UP), led by Professor Bill O'Neill at Cambridge, has now moved on to become a truly world leading highly vibrant research community in the ultra precision field. Bill's own style and enthusiasm has shown through and made this CDT recognised around the world for technical excellence, innovation and novelty. The sponsoring organisations provide evidence to the broad demand for ultra precision technologies. The CDT delivery team at the Institute for Manufacturing at Cambridge supported by Cranfield University precision engineering staff and measurement experts at the National Physical Laboratory have formed a partnership that provides a unique UK facing ultra precision engineering research capacity.

We were delighted that the Royal Academy of Engineering provided support for the Centre's educational outreach programme Watch It Made®. The Academy, together with Vauxhall Motors, provided funding and facilities to allow over five hundred school children between 10-13 years old the opportunity to practice precision engineering by manufacturing a personally designed watch. We are very hopeful this "learn by proudly engineering your own product of quality" is a mode for enthusing the next generation of engineers.

We have progressed significantly during this 4th year. Achievements against our KPI's including those of quality publications and invited keynotes look well on track. Clearly, success in our final year will require even greater attention to detail, partnership building and the multidisciplinary research needed for creating ultra precision production machines, devices and processes. We'd welcome your thoughts on any aspects described in this annual report.

Professor Paul Shore FREng
Principal Investigator

National Strategy Programme Development

The EPSRC Centre in Ultra Precision continues to develop its National Strategy Programme in Ultra Precision. Its aim and ambition is the creation of a thriving community networking across academia and industry, supported by information services and collaboration opportunities. This is achieved through building on the Centre's aim to create ultra high precision manufacturing processes and tools that can make products with nanoscale precision.

The National Strategy Programme's key strategy output will be to create a self-supporting UK national network, acting as an ultra precision knowledge 'hub', through significant engagement with UK industry delivering research specific meetings, technical workshops, industrial short courses and developing its database of UK ultra precision facilities and equipment.

The key elements of the National Strategy Programme include:

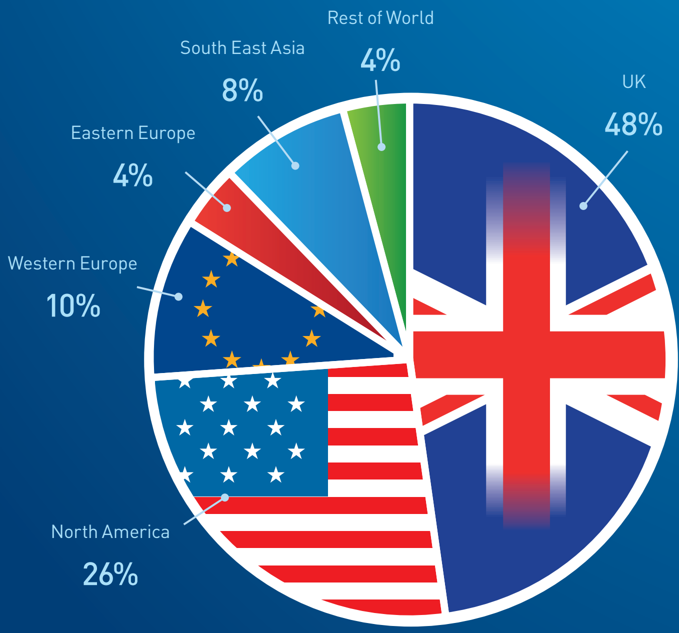
- Ultra Precision Web Services
- UK Ultra Precision Network
- Educational Programme
- Translation to Wealth

Ultra Precision Website and Social Media

The Centre's website **ultraprecision.org** is the Centre's primary resource for informing the ultra precision community and the general public about its complete spectrum of research activities and publications, the National Strategy Programme, UK ultra precision database of facilities and equipment, news and events and linking into the Centre for Doctoral Training in Ultra Precision led by the University of Cambridge.

The traffic to the website continued to increase throughout the year, although as expected, slowed in the summer. Despite this, it still managed to exceed 1 million hits in December 2015. Although the overall number of hits was slightly lower in 2015 (down 3% from 2014), the number of distinct visitors was up by 15%, suggesting that returning visitors have located page references and do not need as many page hits to obtain the information they are looking for.

International engagement is quite high via the web portal, with just over 50% of visitor site hits coming from outside the UK.



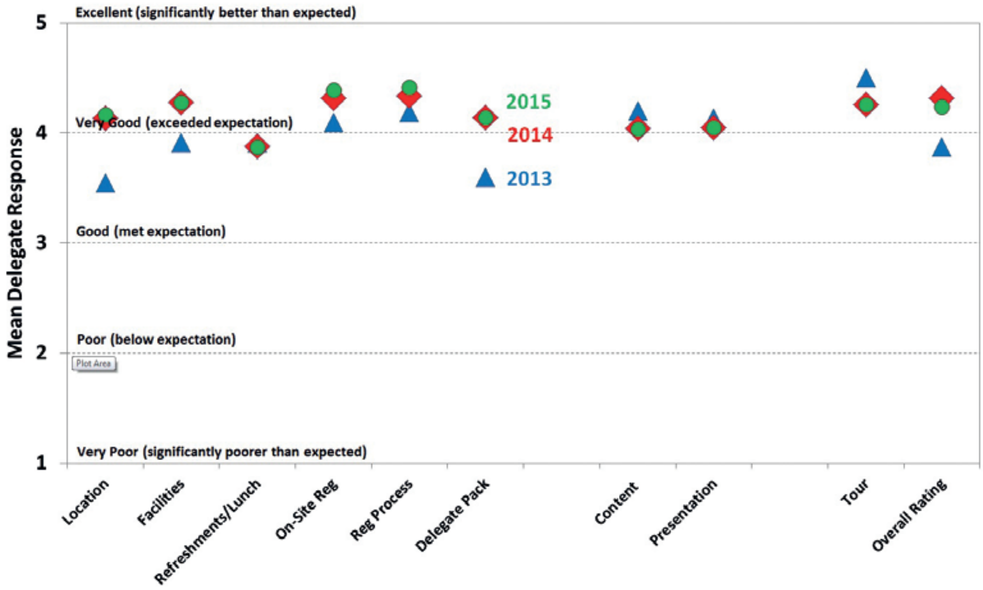
Geographic distribution of website visitors by hits
(January to October 2015)

Social media engagement has also grown over the year, strongly via Twitter with unexpected publicity benefits in many web based journals, blogs and some print media. The Centre exceeded 3000 tweets in 2015 and the number of followers of the **@UPrecisionUK** username continues to rise.

Outreach Networking Events

As part of the *International Year of Light* in 2015, the Centre was able to have 3 of its organised outreach events registered to be part of the UK's celebration of this UN year-long celebration. Events included the *Prestige Lecture James Webb Space Telescope*, presented by Prof Gillian Wright, MBE, FRSE of the **UK Astronomy Technology Centre** at **Cranfield University** in March 2015; *Optical Demands of Astronomy* at the **UK Astronomy Technology Centre**, Edinburgh in June 2015 in collaboration with **Andor** and *Laser Processes in Ultra Precision Manufacturing* at the *Photonex 2015 Exhibition*, Coventry in October 2015. The latter event was held in collaboration with the **EPSRC Centre in Laser-Based Production Processes** led by **Heriot-Watt University**. The Centre aims to continue its collaboration and sponsorship of outreach events in 2016 with the ultra precision community, to enhance delivery of its high quality events.

The events continued to be well attended; in fact overall attendance was higher from 2014, rising from an average 48 delegates per event to 62 in 2015. The delegate feedback continues to show the events are exceeding expectations in nearly all measured categories.



Mean delegate feedback responses for all networking events from 2013-2015.

National and Global Outreach

2015 events continued to garner interest from industry and as the programme was slightly more varied, the Centre met more new UK and overseas companies that previously had not been engaged with the Centre. This has taken the total number of businesses that the Centre has engaged with at some level to in excess of 500. A Customer Relationship Management (CRM) database was introduced in 2015 to help track engagement and to make it easier to identify businesses that wish to engage more directly with the Centre's research activities.

Organising networking events in the UK within the ultra precision community, rather than expecting the community to come to the Centre, has resulted in a broad geographic spread of engaged businesses around the whole of the UK. This is helping to demonstrate the true national spread of the ultra precision community in the UK and shows how the Centre is helping to bridge geographic boundaries and illustrates a UK wide impact for its activities.

National distribution of UK businesses who have engaged with the Centre

Outreach

External events – the Centre attended since March 2015

Our own events

May 2015

National Manufacturing Debate

Cranfield University, UK.

This annual event hosted by **Cranfield University** brought together manufacturing professionals from a range of sectors to discuss and debate current challenges in the industry.

The event encouraged networking and collaboration across the sector to enable continued and long-term growth. The 2015 topic was "How do we develop the capability for effective reshoring to the UK?"

June 2015

euspen's 15th International Conference and Exhibition

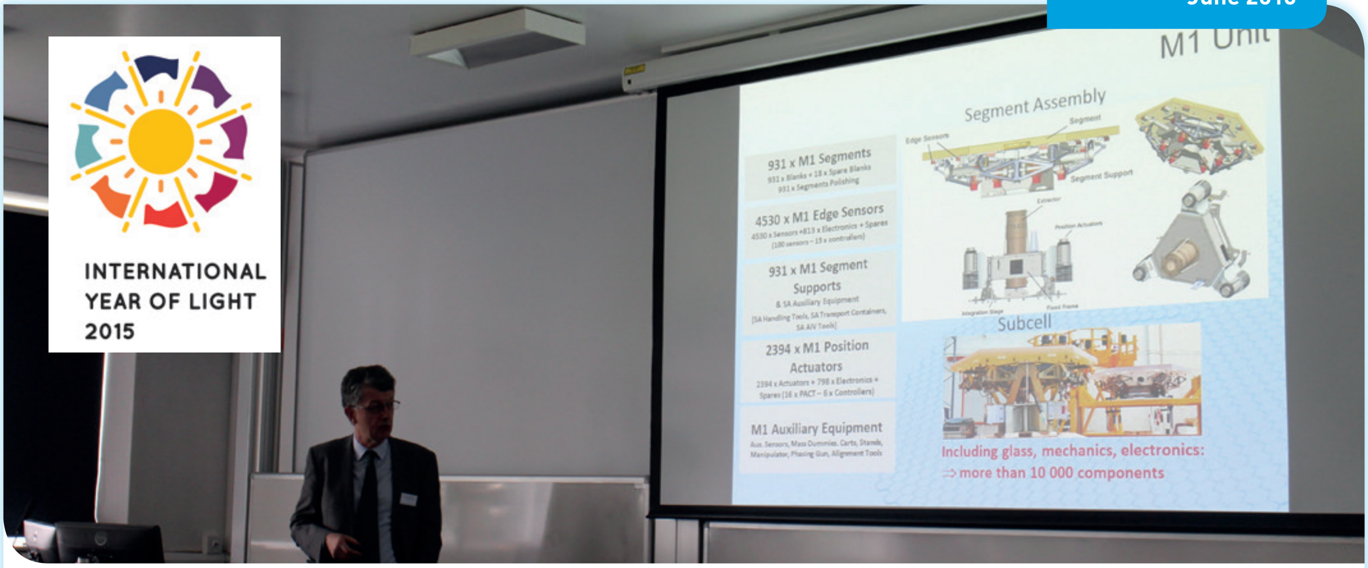
Leuven, Belgium.

The Centre exhibited at *eu**spen**'s 15th International Conference and Exhibition* held in Leuven, Belgium 1-5 June 2015 as part of a Centre organised UK cluster stand with Queensgate Instruments. PhD researcher, Jonathan Abir from **Cranfield University** also presented a poster at the conference.

This event showcased the best international advances in precision engineering fields such as additive manufacturing, medical products, micro-biology, nano and micro manufacturing, metrology, mechatronic systems and control, renewable energy technologies and ultra precision machines.

UK cluster exhibition with the Centre and Queensgate Instruments

June 2015



Optical Demands of Astronomy

Edinburgh, UK.

This event was hosted by the **UK Astronomy Technology Centre**, Royal Observatory, Edinburgh in June 2015. *Optical Demands of Astronomy* was organised by the Centre, in collaboration with **Andor** with the aim of bringing together the UK's commercial optical, high-resolution sensor and controls businesses with the relevant science and research communities to discover what is happening within their various different worlds, and how these can be coupled together to create more business for the UK in these areas and how this can benefit the wider UK optics community.

September 2015

4th Annual EPSRC Manufacturing the Future Conference

Cambridge, UK.

The 4th *EPSRC Manufacturing the Future Conference* was hosted by the **Institute for Manufacturing, University of Cambridge** on 17 and 18 September 2015, where some of the UK's leading academics, industrialists and senior government representatives discussed how new research and government programmes can support the needs of the UK's key manufacturing sectors.

All speakers considered how academic research is already having an impact in priority areas and what more needs to be done to ensure the UK improves its competitiveness in key sectors in the medium and long term. Day one of the conference focused on four main themes: processes and technologies; manufacturing systems; operations networks; and how to support the development of emerging technologies and industries. Day two included presentations from the EPSRC funded Centres for Innovative Manufacturing on how the UK's leading research teams are working with industrial partners to support the commercial development of new manufacturing research. Centres also had the opportunity to exhibit at the conference.

October 2015

Laser Processes in Ultra Precision Manufacturing

Coventry, UK.

The Centre held this event at the Ricoh Arena, Coventry in October during the *Photonex 2015* exhibition in collaboration with the **EPSRC Centre in Laser-Based Production Processes**. The event aimed to update industry with some of the techniques being developed by UK research groups that are applying laser methods to fine-feature (micron and sub-micron) production. It was also an opportunity for businesses to discuss the techniques they are using to solve fine feature issues and to connect with researchers who may be able to help them solve some of their current manufacturing problems. Prof Bill O'Neill, Director of the Centre for Doctoral Training and Karen Yu, PhD researcher at the **University of Cambridge**, presented their research at the event.

Delegates also had the opportunity to attend the exhibition during breaks, taking advantage of various exhibitors at *Photonex 2015*.

> **“Queensgate has had significant benefit from the outreach programme provided for SME’s. Shared stands at the Precision Fair in Veldhoven November 2014 and euspen Leuven in June 2015, halved the cost of exhibiting and provided a cost effective and convenient transportation of exhibition material.”**

Alison Raby, Queensgate Instruments

December 2015

Dr Chris Sansom (fifth from left) with event speakers

Solar Thermal and Concentrating Solar Power: Technology and Applications

Cranfield University, UK.

The Centre was pleased to co-organise this event led by Dr Chris Sansom, Associate Professor in Concentrating Solar Power in the **Precision Engineering Institute** at **Cranfield University**.

Solar Thermal (ST) and Concentrating Solar Thermal Power (CST/CSP) technologies provide many challenges for engineers in the UK including the optimisation of manufacturing methods to reduce costs and the pursuit of new applications. The day included presentations from academic and industrial experts based in the UK and Europe, providing a platform for discussion of how the UK can increase its activity in this truly global market.

The event was sponsored by the EU funded STAGE-STE project whose aim is to encourage collaboration between all stakeholders in the field of solar thermal energy technologies.

Cranfield University is the sole UK representative on the EERA-Joint Committee on CSP which steers EU research in CSP, and has been approved through the DECC Technical excellence Framework as a supplier of solar thermal research and manufacturing technology.

Educational Outreach

March 2015

Prestige Lecture

Cranfield University, UK.

The Centre’s 2015 prestige lecture *James Webb Space Telescope* was presented by Prof Gillian Wright MBE, FRSE, Director of the **UK Astronomy Technology Centre**, Edinburgh at **Cranfield University** in March 2015.

The James Webb Space Telescope (JWST) is NASA’s flagship mission for astrophysics in the coming decade, and is designed to be the scientific successor to Hubble. It will be the largest and most technically ambitious telescope ever flown, requiring a deployable mirror and massive sunshield to cool the telescope to just 40K. Due for launch in 2018, JWST will enable scientists to study the evolution of galaxies at the furthest reaches of the universe and determine chemical compositions of planets in other solar systems.

The talk described the science that JWST will do together with the technologies and the engineering on both small and large scales that are fundamental to the mission success. It also described the European participation in the mission development and in particular the Mid-Infrared Instrument, MIRI, which has been led from the UK. An overview of the current status of the mission development was presented, giving a perspective and flavour of the momentous JWST programme.

April 2015

Group project team with supervisor Dr Paul Comley and Cherie Denton, Community Relations Coordinator, Vauxhall Motors

MSc Group Project Presentation Day

Cranfield University, UK.

Cranfield University's Manufacturing Group Project Presentation Day took place in April 2015, showcasing projects from the manufacturing, materials and design programmes.

Full time students spent three months in groups delivering on strategic projects, many supported by industry. The presentation day provided an opportunity for the students to demonstrate the value that they have brought to sponsoring clients as well as an opportunity for networking.

The EPSRC Centre in Ultra Precision supported the group project Watch it Made® Go Mobile which looked at creating a mobile version of the Watch it Made® watch making experience.

As part of this group project, a partnership with **Vauxhall Motors** in Luton, Bedfordshire was established, who provided a vehicle for the watch making experience to be delivered at various venues. The group project video is available on YouTube: https://www.youtube.com/watch?v=mrCxmVN3OWc

Group project members were:

- Mr Stephen Ajadi
- Mr Julien Haba; Ms Clotilde Lebrun
- Ms Ramóna Péter
- Ms Bich-Lan Phan
- Mr Bertrand Richer
- Mr Robbie Wang

They were supervised at **Cranfield University** by Dr Paul Comley and Professor Paul Shore.

May 2015

Ultra Precision Conference

Institute for Manufacturing, University of Cambridge, UK.

First year MRes students of the Centre for Doctoral Training in Ultra Precision at the **University of Cambridge** organised and hosted the *Ultra Precision Conference* in Cambridge to showcase advances in ultra precision engineering in fields such as additive manufacturing, nano and micro manufacturing, metrology, mechatronic systems and control, and ultra precision machines. The event was designed to provide an opportunity for industrialists and academic researchers to share their latest ideas and to explore future collaborative opportunities in the field of ultra precision engineering.

Speakers were from the **EPSRC Centre for Innovative Manufacturing in Ultra Precision, Cranfield University, University of Nottingham, Oxford Lasers, Heriot-Watt University, Oxford Instruments, National Physical Laboratory, Cardiff University, University of Huddersfield, University of Bristol, University of Southampton, PI UK Ltd** and **Zeeko Ltd.**

The PhD research students also presented their research to the audience and the conference also provided the delegates the opportunity to network with some exhibitors present which included **Lambda, PI GmbH, Orlin Technologies** and **Aerotech**.

July 2015

euspen Challenge

Stockholm, Sweden.

euspen Challenge is an annual international competition organised by eu**spen** which identifies students with potential to be future leaders in the field of precision engineering and nanotechnology. The event provides students with the tools to embrace and apply current and newly acquired skills in a constantly changing and demanding market. Working in culturally diverse teams, students have access to respected industry to develop their commercial awareness.

In 2015, the event was held at **KTH Royal Institute of Technology**, Sweden in collaboration with **Hexagon Metrology Nordic AB**, Sweden. The challenge was to design and build an optical coordinate measurement machine to achieve maximum accuracy with low economic budget. The challenge addressed the appearance and functionality of the prototype; scientific and methodological aspects; innovative aspects; economic and production aspects; followed by a presentation.

James Norman, a PhD researcher within the Centre at **Cranfield University** got through the national heats in early 2015 and went on to participate in the eu**spen** *Challenge* in Sweden, 7-9 July 2015.

James Norman (left) with eu**spen** *Challenge* team members

September 2015

2015 short course cohort with Precision Engineering Institute staff

Precision Engineering Industrial Short Course

Cranfield University, UK.

The Centre held its annual *Precision Engineering Industrial Short Course* at Cranfield 21-25 September 2015. Delegates were from **Cranfield Precision, The Manufacturing Technology Centre, SKF (Sweden), Holroyd Precision, Atlantic Diamond Ltd (Ireland), SIRIM Berhad (Malaysia), FANUC UK, Cranfield University** and the **University of Strathclyde**.

This year, lab equipment demonstrations were provided by the Centre's community members **Armstrong Optical** demonstrating metrology equipment, and **Physik Instrumente (PI)** demonstrating nano positioning equipment.

September 2015

MSc Research Exhibition

Cranfield University, UK.

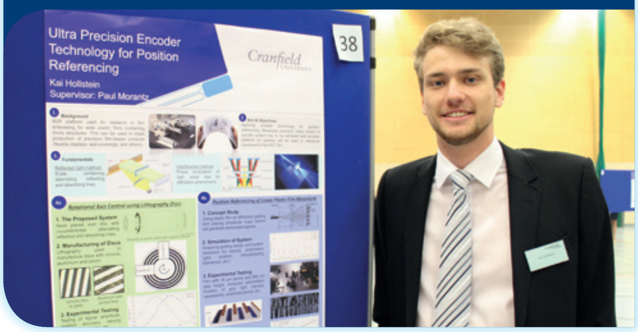
Masters students from the School of Aerospace, Transport and Manufacturing at **Cranfield University** showcased their individual MSc project research in September 2015. This poster presentation day demonstrated world-class capabilities in manufacturing, materials and design disciplines.

MSc students Kai Hollstein, Suphansa Lieotrakool and Vicente Rivas Santos undertook their MSc individual research projects at within the EPSRC Centre in Ultra Precision. Projects were:

- Ultra Precision Encoder Technology for Position Referencing (Kai Hollstein)
- Imprinting Lithography for Flexible Transparent Plastic Substrate by using Copper Mould in Mass Production (Suphansa Lieotrakool)
- An Approach to Smart Temperature Measurements on Advanced Materials for Optical Fabrication (Vicente Rivas Santos).

Overviews of these projects are available on the Centre's website: http://www.ultraprecision.org/research/research-portfolio/

Kai Hollstein, MSc in Manufacturing Technology and Management



“I thoroughly enjoyed the stimulating course and learning from people who are in such command of their specialised subjects.”

Mícheál Ó Ceallaigh, Atlantic Diamond Limited, Precision Engineering Industrial Short Course delegate, September 2015

October 2015

Samuel Whitbread Academy Careers Fair

Shefford, Bedfordshire, UK.

The Centre was invited to the annual Samuel Whitbread Academy Careers Fair in October 2015. This fair is open to students and parents, with a large range of local and national employers, colleges and universities in attendance to provide valuable advice and guidance on career paths. Dr Paul Comley and Enza Giaracuni attended the fair and provided advice on engineering routes, including the forthcoming apprenticeship opportunities soon to be available at Cranfield University.

2015

Work Experience/Internships

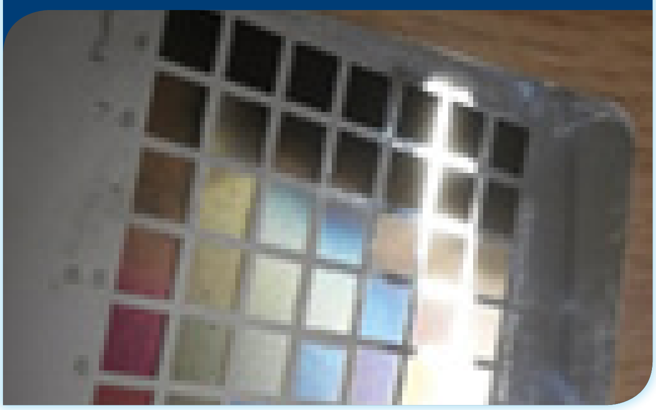
University of Cambridge, UK.

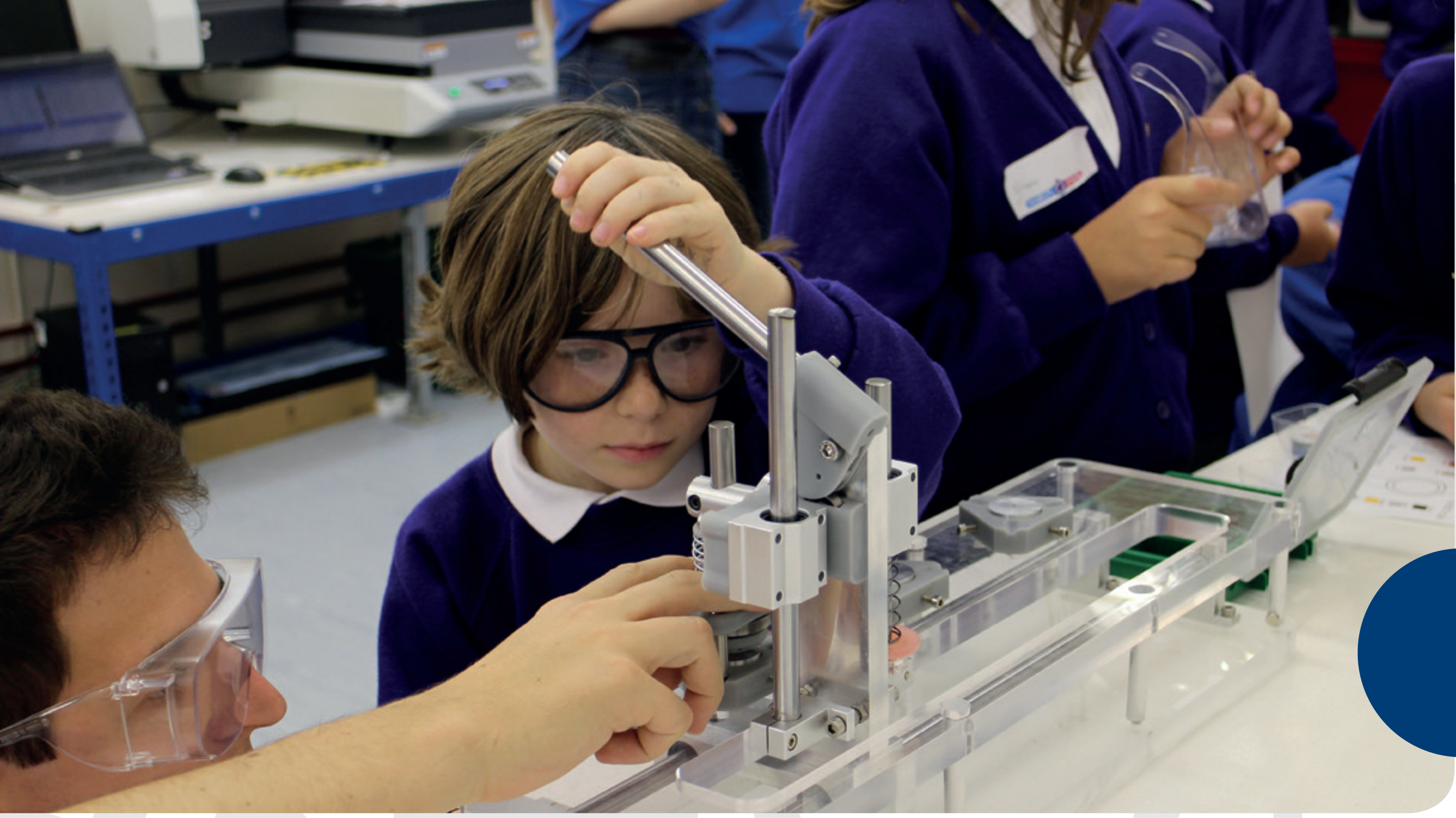
Silas Talbot from **King Edward VII School**, Sheffield visited the **Centre for Industrial Photonics** at the **University of Cambridge** for a week during school summer holidays. Silas worked on the G3 marking laser to identify the correct parameters to produce a blue hue when marking a stainless steel substrate. He achieved this and produced a set of cards with parameters and resulting colours for our reference.

Alpay Hassan and **Asad Rahman** from **The City Academy**, Hackney also visited the **Centre for Industrial Photonics** at the **University of Cambridge** for one week in August 2015. They used the SPI G3 laser marker to try and obtain a parameter chart for colour marking on stainless steel. This is something that is already achievable; it is currently believed that the colours appear from the different oxide layers of different thicknesses and compositions. However, it is an extremely sensitive process and with at least 6 parameters to explore, including power, pulse shape, repetition rate, scanning speed, scanning line distance, and focal position, finding a reliable set of parameters for each colour remains a difficult problem. While a reasonable quality of red, orange, yellow, green and pink were already available from previous work, blue remained un-obtained.

Alpay and Asad managed to find the parameters for blue, though it is extremely sensitive to small errors in parameters. The results were tabulated in a single piece of stainless steel where for a given pulse shape, repetition rate, scanning speed, and focal position, the scanning line distance and laser power were altered. With Silas Talbot’s results and some of Jiho Han’s (PhD researcher at the **University of Cambridge**), a full spectrum of colour is now available at a reasonable marking speed.

Colour marking on stainless steel cards with the SPI G3 laser marker. The grid shows the results for varying laser power and hatching distances.





Watch it Made®

Watch it Made® is the Centre's educational programme conceived by academic staff to create an engineering based activity to enable young learners to experience the unique "pride of producing" that only engineering can offer; the aim being to enthuse children in STEM subjects prior to their GCSE subject selections.

The Watch it Made® experience is led by former **Cranfield University** MSc student, Armand Didier, and is delivered in a dedicated Manufacturing Learning Studio based at the Precision Engineering Institute at **Cranfield University**. Children begin by learning about watches and designing their own watch. They then move through a number of manufacturing cells to produce parts. These include a UV ink jet printer to produce the watch face, a precision lathe for the watch body, and a micro-milling machine to engrave the watch back. During each of the stages, the children are involved with the set-up and control of the CNC machine tools. Finally, the children assemble all of their manufactured watch components, together with some pre-supplied parts e.g. hands, watch glass and strap. At the end of the session, all of the children leave with their own personalised timepiece. The workshops are run with a group of up to 10 children.

Additional funding secured through the EPSRC Impact Acceleration Account has enabled more schools to participate in the workshops. In April 2015, Watch it Made® won further funding through the **Royal Academy of Engineering**'s public engagement grant scheme, *Ingenious*, which supports projects across the UK that creatively engage the public with engineers. Together, this funding has enabled over 500 UK school children to participate in the Watch it Made® experience, taking home their own designed and manufactured quality watch.

Professor Sarah Spurgeon FREng, Chair of the *Ingenious* funding panel and Professor of Control Engineering and Head of School, University of Kent, said: *"The Royal Academy of Engineering's Ingenious projects are finding new and innovative ways to get the public – whether student, family, or adult-audiences – engaged with engineering. Our projects don't just showcase the diversity of engineering – they also give the public a meaningful opportunity to interact with engineers, ask questions and share their views."*

Ingenious is funded by the **Department for Business, Innovation and Skills**. A full list of projects funded by the scheme in 2015 can be found at the following link: http://www.raeng.org.uk/publications/other/ingenious-awards-round-9-2015

ROYAL ACADEMY OF ENGINEERING

"The children (and staff!) absolutely loved it, a fantastic opportunity that I am sure they will remember for a long time. They have come in today proudly wearing their watches. The team engaged the children so well and were so encouraging towards them as well as enthusiastic about their specialism that it rubbed off on the children and our constant quest to raise the aspiration of our children was well backed up. A thoroughly enjoyable session and I will be spreading the word with other schools."

Mrs Busari, Deputy Head, St James Church of England Primary School, Northamptonshire.

VAUXHALL
Proud Sponsors of Watch it Made

Vauxhall Motors staff at the Watch it Made® workshop with Cardinal Newman Catholic School, Luton

Vauxhall Motors (Luton) has supported Watch it Made® through sponsorship, initially providing a vehicle for the group project Watch it Made® Go Mobile, enabling the experience to be delivered outside Cranfield. Subsequently they funded a watch making experience for **Cardinal Newman Catholic School**, a school near to their Luton manufacturing site. Denis Chick, Director of Communications and Cherie Denton, Community Relations Coordinator at **Vauxhall Motors** attended the workshop, gaining an insight of the full activities the experience offers. They were positive about the programme and continued engagement with Watch it Made®.

Walton High pupils at Hexagon Metrology 3D scanning their watches

Hexagon Metrology located in Milton Keynes sponsored local school, **Walton High**. Following the workshop, the pupils enjoyed an afternoon at **Hexagon Metrology** learning about portable scanning equipment and component measuring.

In March 2015, experiences took place at the *Cambridge Science Festival*, **University of Cambridge**. As part of the 60th anniversary of atomic timekeeping at the **National Physical Laboratory** (NPL) in Teddington, Watch it Made® were invited to the site during half term week in October to offer local school pupils the opportunity to learn about engineering through design and manufacture of their own watches. Philip Greenish CBE, Chief Executive of the **Royal Academy of Engineering** and Professor Dame Ann Dowling DBE, FREng, FRS, President of the Royal Academy of Engineering, visited the event, taking the opportunity see the experiences being delivered and spoke with the pupils about their watch making experience.

Since Watch it Made® was launched at the *3rd Annual EPSRC Manufacturing the Future Conference*, Glasgow, September 2014, it has hosted some 600 experiences for school aged children from **Cranfield University, University of Cambridge** and **NPL** staff, together with primary and secondary schools throughout Bedfordshire, Buckinghamshire, Northamptonshire and Hertfordshire. Schools include: **Samuel Whitbread Academy, Arnold Academy, Goldington Academy, Bedford Modern School, Bushfield School, Hastingsbury Business & Enterprise College, Holywell School, Biddenham International School & Sports College, Woodland Academy, Swanbourne House School, Cardinal Newman Catholic School, Walton High School, Beauchamp Middle School, Emerson Valley School, Oakgrove School, St James Church of England Primary School, Newnham Middle School, Ashton Church of England Middle School, Ousedale School, Margaret Beaufort Middle School, The Priory School, St Paul's Catholic School, Parkfields Middle School, The Highfield School** and **Deanshanger Primary School**.

Further details about all the watch making experience can be seen online: http://www.ultraprecision.org/national-strategy-programme-in-ultra-precision/academic-outreach/

Year 6 pupils and staff from St James Church of England Primary School, Northamptonshire

To find out more about Watch it Made®, please visit

www.watchitmade.org

Further Outreach Activities

The Centre's National Strategy Manager, Martin O'Hara continued to be active in attending various one day meetings and events which included the *National Manufacturing Debate* (**Cranfield University**), *National Electronics Week* (Birmingham), *Micro Nano MEMS* (Birmingham), *Engineering Design Show* (Coventry), *Advanced Engineering UK* (Birmingham) and industry days at **Yamazaki Mazak UK Ltd** (Worcestershire), **Fronius UK** (Milton Keynes), **Citizen Machinery UK** (Bushey), and **Seco Tools** (Warwickshire).

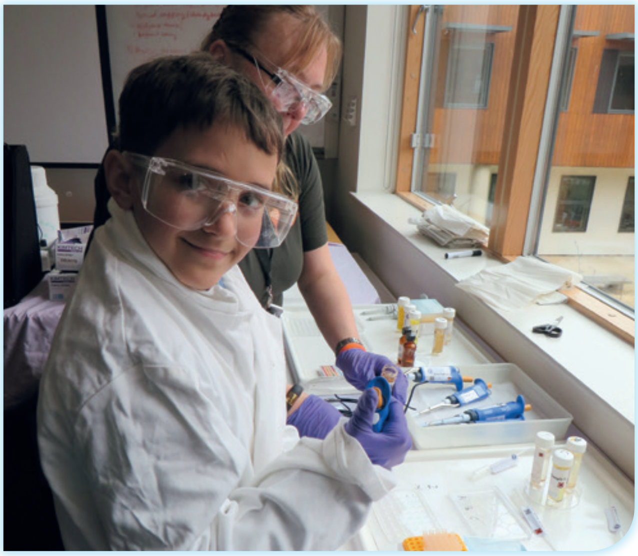
Professor Tim Wilkinson attended the *European Conference on Liquid Crystals* at the **University of Manchester** in September 2015. He was involved in the hands-on interactive exhibit on the science and technology of liquid crystal lasers as part of a public science open day in Manchester.

Visits were hosted by the Centre for the **UK Fusion Advisory Board, Lawrence Livermore National Laboratory, RMIT University Melbourne** (Australia), **Osaka University** (Japan), **EPSRC Centre in Laser Based Production Processes, Renishaw plc, Innovate UK, Sandvik Tools, AWE, Double-R Controls, DMG Mori, Wave Optic, NSK Ltd**, and the **Sino-Bridge International** delegation from China.

Martin O'Hara with the Sino-Bridge International delegation from China

The Centre hosted laboratory equipment demonstrations by industry at Cranfield, which provided staff and students the opportunity to see various technical equipment on the market and they were also able to bring samples for testing. **Acutance Scientific** demonstrated a 3D optical profiler, and during the week of the **Precision Engineering Industrial Short Course** in September, **Physik Instrumente** (PI) demonstrated micro and nano positioning systems and **Armstrong Optical** demonstrated metrology instrumentation.

The **Institute for Manufacturing, University of Cambridge** hosted the Manufacturing Zone as part of the *Cambridge Science Festival* in 2015. This event was also part of the *International Year of Light* celebrations. The zone consisted of a number of hands on exhibits and laboratory demonstrations, many focusing on ultra precision technologies that were enjoyed by around 1500 visitors to the event.



Future Outreach Events

The Centre plans to attend exhibitions this coming year; the *National Manufacturing Debate* at **Cranfield University** in May 2016 and eu**spen**'s *16th International Conference and Exhibition* in June 2016 at the **University of Nottingham**.

Planning for Centre organised outreach events in 2016 are in progress and include *Tool and Workpiece Fixturing* hosted by **Yamazaki Mazak UK Ltd**; *Optical Materials Day* at **Cranfield University**, a co-organised event with **Optence e.V.** (Germany) in collaboration with **Schott AG**, **Heraeus GmbH** and **Hellma Materials GmbH**; *Future Challenges of Instrumentation and Control in Ultra Precision Manufacturing* hosted by **Renishaw plc**, *Laser FIB: Industrial Applications* hosted by the **Institute for Manufacturing, University of Cambridge** and finally, *The Future of Precision Engineering*, to be held at the **Academy of Medical Sciences** in London.

The *Precision Engineering Industrial Short Course* will be delivered in September 2016 at **Cranfield University**, plus the *Energy Beam Processing Short Course* which will take place in February 2016 at the **Institute for Manufacturing, University of Cambridge**.

Sustainability

As the Centre enters its final year, it has tried some commercial activities such as overseas exhibition cluster stands and looked at running a UK membership model to support future outreach. The only approach that would secure adequate levels of financial support to continue the programme of activities we have so far achieved is another funded programme. To this end, the Centre has submitted an expression of interest for a Manufacturing Research Hub in the next round of EPSRC bids, and in 2016 we hope to be pursuing this further to maintain the impetus so far achieved in the UK ultra precision community.

Presentations

A series of oral and poster presentations, were presented at various conferences by Centre staff and researchers:

Abir, J., Morantz, P. and Shore, P. (2015). *"Position errors due to structural flexible modes"*

eu**spen**'s 15th International Conference and Exhibition, 1-5 June 2015, Leuven, Belgium. (Poster presentation)

Diaz, A. (2015). *"A brief introduction to ultra precision engineering"*

Presented to 6th form students at Stationers' Crown Woods Academy on 30 April 2015, London, UK.

Dong, T. (2015). *"Evaluating femtosecond laser ablation of graphene on Si02/Si substrate"*

International Congress on Applications of Lasers & Electro-Optics (ICALEO 2015), 18-22 October 2015, Atlanta, USA.

Dong, T. (2015). *"Laser processing of graphene for device application"*

brainSTEMMs, Lucy Cavendish College, 19 November 2015, University of Cambridge, UK.

Morantz, P. (2015). *"Control of cooling and process fluids with traceable accuracy and milli-kelvin precision"*

High-Tech Systems 2015, 's-Hertogenbosch, 25-26 March 2015, Netherlands.

Morantz, P. (2015). *"State of the art of very high precision measurements in metrology"*

1st PACMAN Workshop (Particle Accelerator Components' Metrology & Alignment to the Nanometre Scale), 2-4 February 2015, CERN Geneva, Switzerland.

Morantz, P. (2015). *"The μ4 diamond machining system"*

Roadmapping Workshop, Micro-machining Research Platform, 22 April 2015, Cranfield University, UK.

O'Hara, M. (2015). *"Large scale (1.4 m wide) roll to roll research platform"*

Plastic Electronics Europe 2015, 28-29 April 2015, Berlin, Germany and at Advanced Engineering UK, 4-5 November 2015, Birmingham, UK. (Poster presentation)

O'Neill, B. (2015). *"Additive manufacturing, a technology set for change?"*

Industrial Laser Application Symposium, 17 March 2015, Chesford Grange Conference Centre, Warwick, UK.

O'Neill, B. (2015). *"Ultra precision machining systems and technologies"*

Laser Processes in Ultra Precision Manufacturing, 15 October 2015, Ricoh Arena, Coventry, UK.

O'Neill, W. (2015). *"Working at the speed of light"*

Lightfest, 25 September 2015, Aston University, UK.
https://www.youtube.com/watch?v=-RfLZRaPNKI&feature=youtu.be

O'Neill, W. (2015). *"Laser based ultra precision manufacturing"*

3rd International Academy of Photonics and Laser Engineering Annual Conference, 2-5 August 2015, Hawaii, USA.

Sanz, C., Cherif, A., Mainaud-Durand, H., Schneider, J., Steffens, N., Morantz, P. and Shore, P. (2015). *"New potential for the Leitz Infinity Coordinate Measuring Machine"*

eu**spen**'s 15th International Conference and Exhibition, 1-5 June 2015, Leuven, Belgium. (Poster presentation)

Yu, K., Sparkes, M. and O'Neill, W. (2015). *"Control system for ultra precision processing"*

Laser Processes in Ultra Precision Manufacturing, 15 October 2015, Ricoh Arena, Coventry, UK.

Yu, N., Jourdain, R., Gourma, M. and Shore, P. (2015). *"Investigation of power dissipation in a collimated energy beam"*

The 6th International Conference of Asian Society for Precision Engineering and Nanotechnology, (ASPEN 2015), 15-20 August 2015, Harbin, China.

Prof Paul Shore presenting the keynote lecture at ASPEN 2015, China

Keynote Presentations

Chu, D. (2015). *"A double sided roll-to-roll system for the fabrication of flexible display panels"*
12th IEEE International Conference on Electronic Measurement & Instruments (ICEMI 2015), 16-18 July 2015, Qingdao, China.

O'Neill, W. (2015). *"Additive manufacturing across the length scales"*
Asian Manufacturing Association 3DP Conference, 1 June 2015, Chengdu, China.

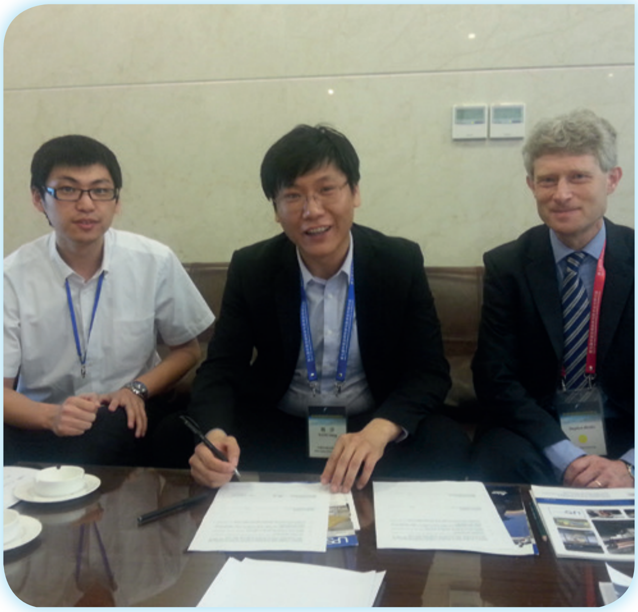
O'Neill, W. (2015). *"Manufacturing challenges in graphene"*
Graphene and Business Conference 2015, 6 November 2015, Cambridge, UK.

Shore, P. (2015). *"μ4 - a compact 6 axes ultra-precision micromachining system"*
6th International Conference of Asian Society for Precision Engineering and Nanotechnology, (ASPEN 2015), 15-20 August 2015, Harbin, China.

Wilkinson, T. D. (2015). *"Nanophotonics for holographic applications"*
PHOTONICA 2015, 24-28 August 2015, Belgrade, Serbia.

International Collaborations

Prof Paul Shore visited China in August 2015, where he presented a keynote lecture at the *6th International Conference of the Asian Society for Precision Engineering and Nanotechnology (ASPEN 2015)*. During his visit he took the opportunity to meet with the **Beijing Institute of Space Mechanics and Electricity (BISME)** to discuss activities based on the memorandum of understanding in place with **Cranfield University** and **BISME** which was signed in May 2014 during the *9th UK-China Workshop on Space Science and Technology*. The collaboration will enable **BISME** and **Cranfield University** to define new methods and instruments for producing many advanced components needed within future space systems. Prof Shore was also able to present the **National Physical Laboratory's** instrumentation business capability at the conference.



Signing the MOU with Mr Yang Yang, Dean of Marketing, BISME (centre) and Nan Yu, PhD researcher at Cranfield University (left) and Dr Stephen Hobbs, Director of Cranfield Space Research Centre (right)

Visiting researcher **Vincent Serantoni** from **The University of Montpellier**, France, worked with the plasma figuring team at Cranfield University through the Erasmus exchange programme for a six month period from March to August 2015. Vincent contributed to the preliminary stage of the design of a control system for the plasma figuring facilities.

Cranfield University's Precision Engineering Institute owns a unique plasma figuring capability to correct large optical surfaces at atmospheric pressure. In the context of ever increasing dimensions of optical components, there is a need for improving the robustness and securing the performance of its Plasma Delivery System (PDS). The current PDS is based on an inductive output L type RF network, Inductively Coupled Plasma (ICP) torch and CNC motion system.

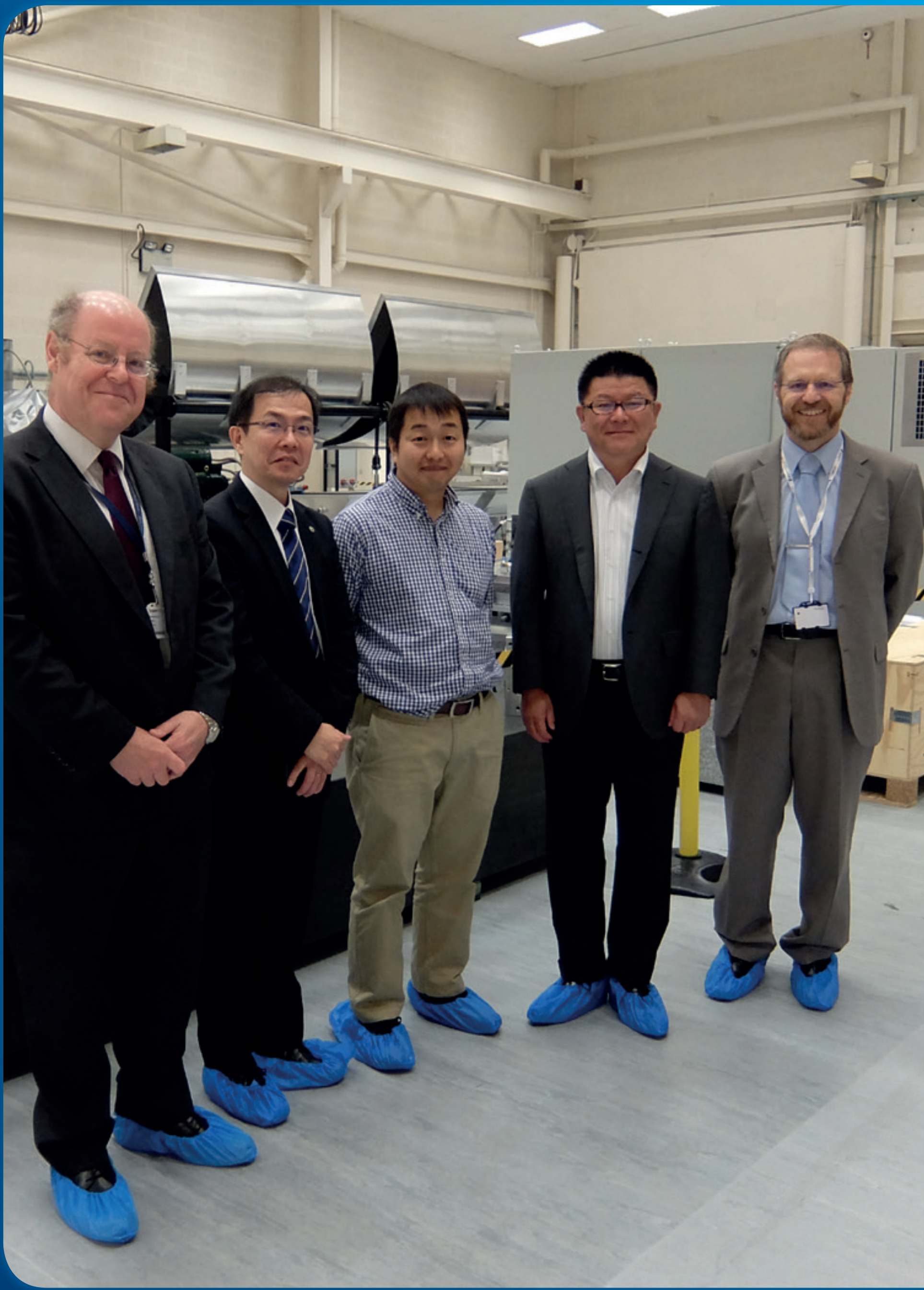
The combination of optical component surface areas and the nature of the sub-aperture plasma tool lead to significant processing duration. The PDS requires deep awareness and fine understanding of the technologies used. Based on the knowledge acquired for the past eight years, Vincent pioneered the creation of a smart control system for the unique PDS that equips the machine Helios1200. This novel control system aims to secure the process determinism and assists the machine operator by tuning some key electrical components of the RF network and monitoring some processing parameters.

Hui Zhou from the **Commercial Aircraft Corporation of China Ltd** joined the Precision Engineering Institute at **Cranfield University** in October 2015 and is continuing this research as his Masters by Research post-graduate degree.

Hui Zhou

Michal Strzelecki, an Erasmus student from the **Wroclaw University of Technology**, Poland, visited the **Centre for Industrial Photonics, University of Cambridge** during the summer for a period of 3 months. He was responsible for CAD designs of housing structures to hold the various Aerotech drivers and electronics in the new ultra precision laser FIB platform. This work contributed to the overall design of the room, ensuring the electronics were placed in easily accessible locations that met health and safety standards.

In June 2015, the Centre welcomed back visitors from **NSK Ltd**, Japan. The Centre is hosting visiting academic **Mr Takashi Yoshimura** of **NSK Ltd** whose research is focusing on the development of the reel to reel bearing system for the Centre's reel to reel platform. Progress meetings were held with Centre staff and Dr Satouru Arai and Dr Kazuo Miyaguchi, Head of Linear Technology Centre at **NSK Ltd**.



Mr Takashi Yoshimura (centre) with colleagues of NSK Ltd, Japan and Cranfield University staff Paul Morantz (left) and Martin O'Hara (right)

Research Platforms

Laser FIB Platform

The laser focused ion beam (FIB) platform has seen much development over the past 12 months. It is being developed to provide an ultra precision production platform capable of offering micro and nano-machining capabilities with in-process metrology for a wide range of materials utilising laser and focused ion beam technologies. The design brief requires length scale machining resolutions for the two principle processing routes at 30nm for the focused ion beam (FIB) and 200nm for the laser processing approach. In order to achieve this, it was decided to adopt a process chain of laser processing followed by ion beam processing, rather than an integrated machine.

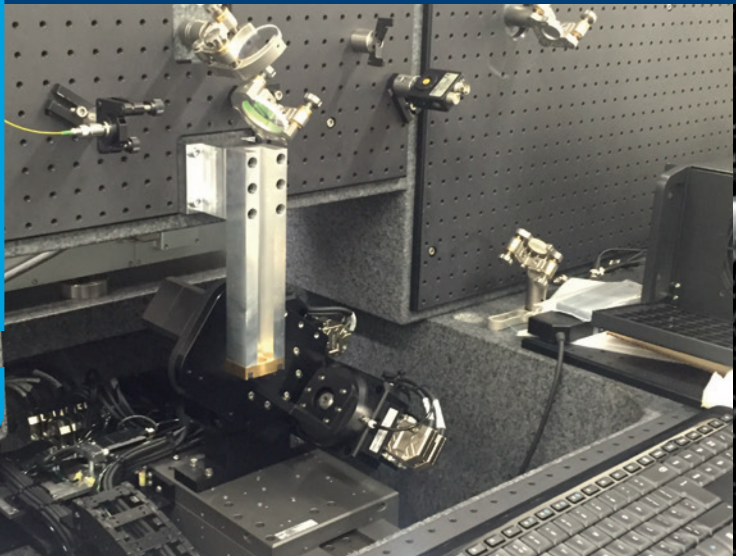
Laser FIB schematic

Foundations of the Laser System

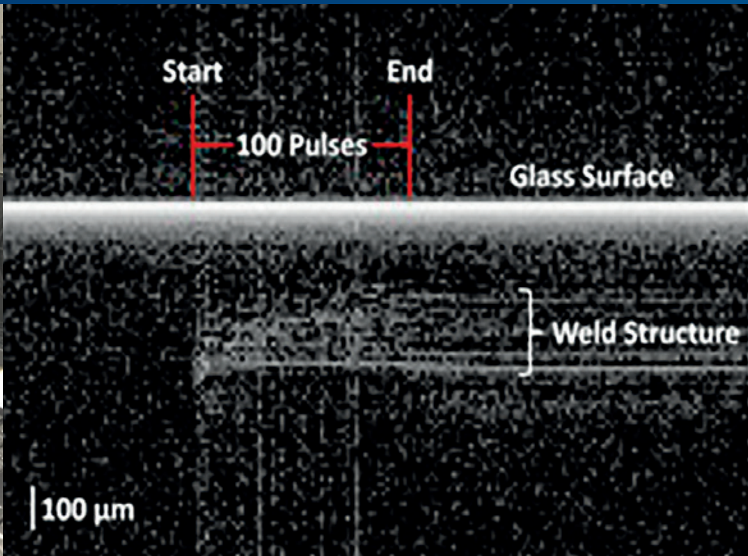
The laser platform consists of an integrated motion system that offers 5-axis positioning with a resolution of 50 nm and positioning stability of 25 nm. A complex optical beam train with picosecond laser and multi-wavelength capabilities at 1060 nm, 532 nm, and 355 nm, is mounted on a bespoke granite bed designed to offer exceptional stability and create a platform on which metrology solutions and processing methods can be employed.

The laser system is in the final stages of completion and has already been used for a number of process trials. The past year has delivered the detail design concepts, construction of the high resolution processing stage for the laser component, and much of the beam delivery systems necessary for high resolution laser processing. Much effort has been applied to the finer details of beam delivery including establishing the capabilities for beam diameter control, power control and beam pointing stability control in addition to finalising the control methodologies and software architecture.

Laser system elements



OCT image of micro glass welding

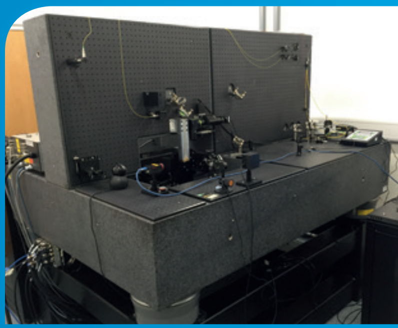


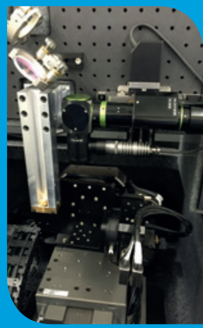
In Process Metrology

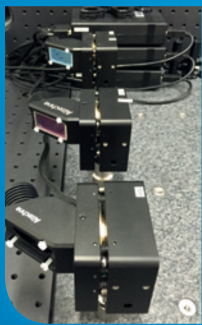
Three different metrologies have been chosen for this system, each targeting a specific area of analysis: optical microscopy provides a low cost ex-situ imaging system for pre- and post-processing analysis, Optical Coherence Tomography (OCT) allows for high speed point inspection, and Digital Holographic Microscopy (DHM) generates in-situ 3-D data. The imaging techniques will work both with and independently of each other and thus allow the overall system to be modular and adaptable to the needs of industry.

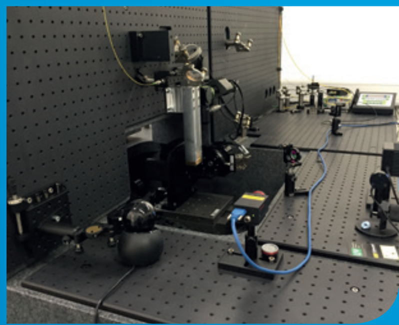
A swept source OCT (SS-OCT) was chosen for the purposes of high speed in-process point inspection. SS-OCT provides 1D depth information at high speeds (> 100 kHz) and is able to image high aspect ratio figures due to the large dynamic range of the signal, giving an axial-resolution of 7.5 μm and a depth of field of 250 μm. The system has undergone extensive development and is currently being used for a variety of in-process measurements in precision machining and glass-to-glass micro welding applications. A prototype DHM system has been constructed to allow for a preliminary characterisation and testing of the various algorithms and resolution limits given by theory. Once complete, the final system will be a triple wavelength unit, with a depth of field of 5 μm, an axial resolution of 50 nm and a lateral resolution of 500 nm.

The laser system is capable of delivering single point laser processing, fast galvanometric scanning and large area holographic imaging utilising a LiCoS phased array mirror. These combined sub-systems offer substantial processing capabilities on a wide range of materials, in addition to delivering process resolutions of around 200 nm using discrete ablation level control techniques that have been developed within the research portfolio programme. Additional work on laser beam parameter and positional control may push the limits of processing resolution down below 200 nm on well-behaved materials like Si.



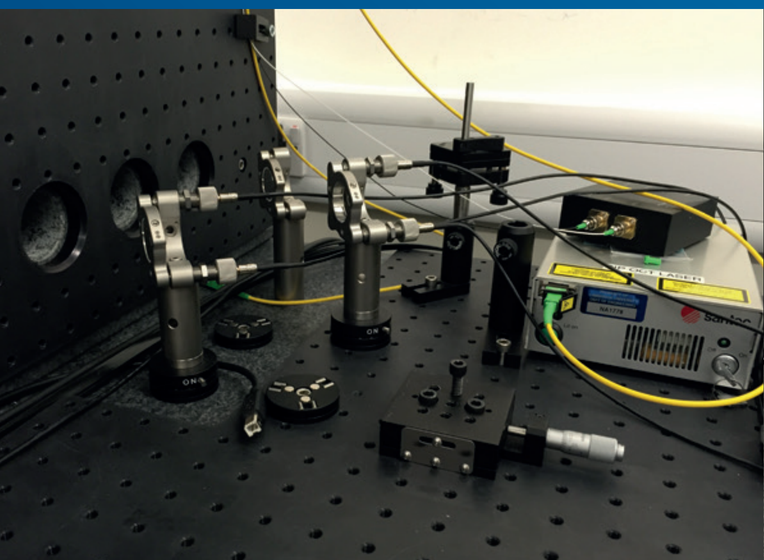


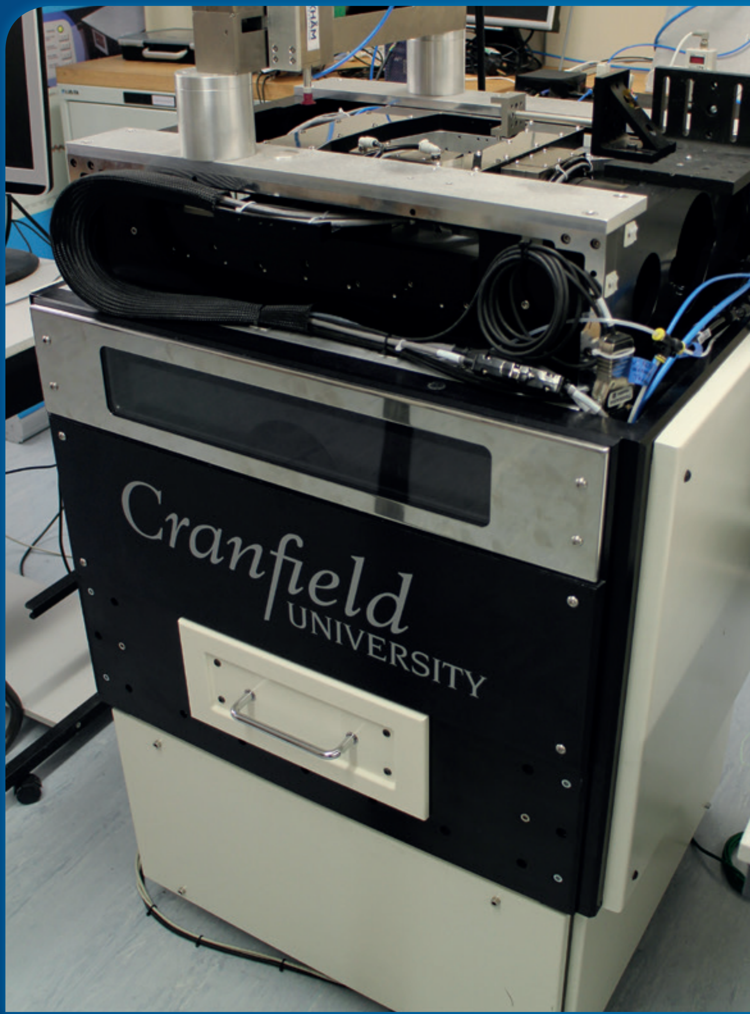




Laser FIB Process Chains

The combined processing steps of the laser system (resolution of ~ 200 nm) and ion beams (resolution ~ 40 nm), should deliver considerable productivity gains compared to single step FIB processing. High resolution Ga+ based FIBs have material removal rates of around 1x10^2 μm^3/min compared to an ultrafast laser which achieves around 1x10^6 μm^3/min for beam diameters of 1 μm. There is a significant benefit in combining the two processing operations in series to establish high throughput ultra precision machining at the nanoscale. The laser system should be able to quickly and accurately add or remove material from a sample wafer, so that FIB machining can be used to finish the process with very high accuracy. The new laser FIB technology components, such as work piece jig, fixtures, and processing pallets are in the final stages of production and will be ready for processing trials in early 2016.





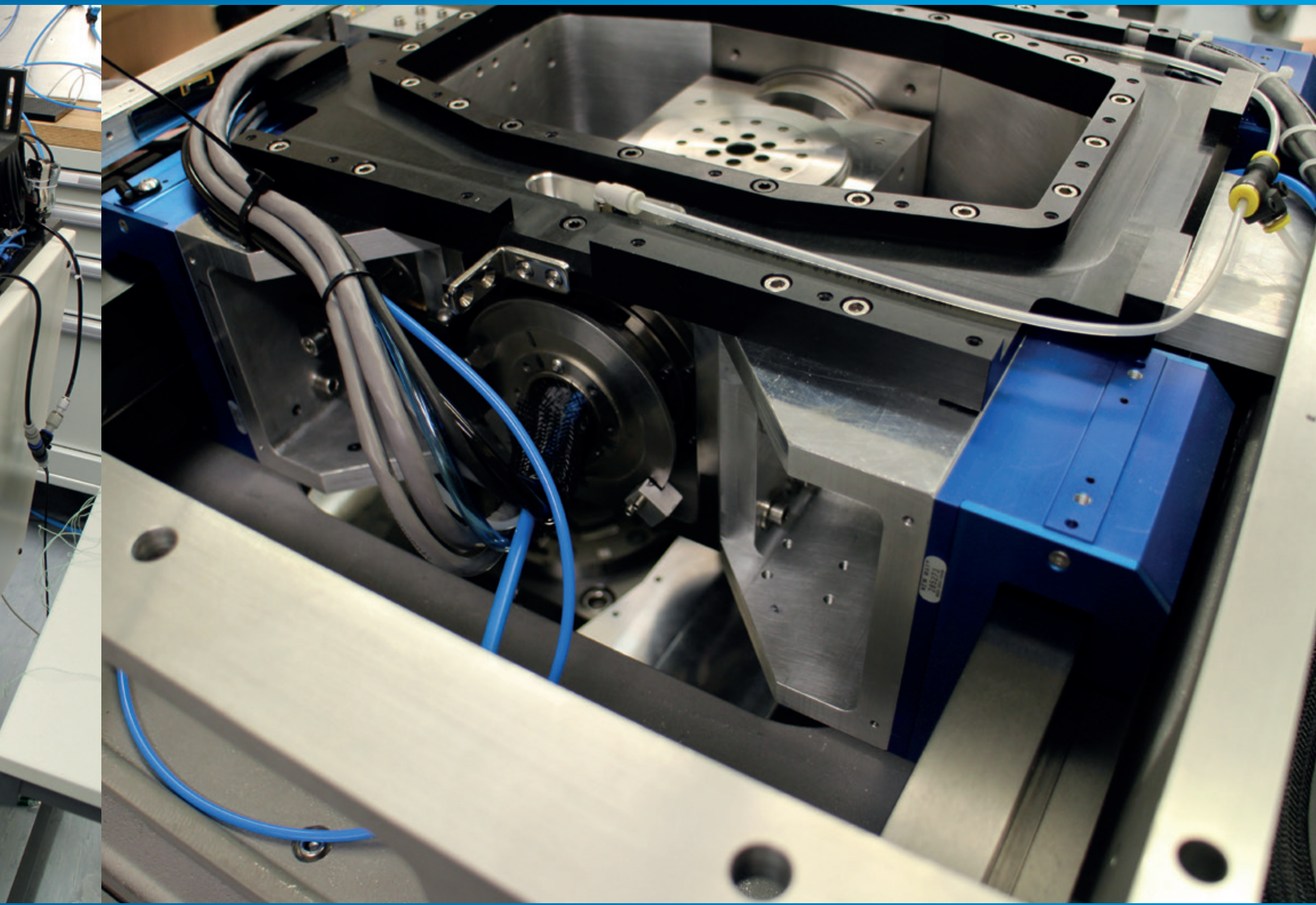
Meso Platform

The meso platform is making significant strides towards becoming a successful commercial machine tool product here in the UK.

During this 4th year, the prototype system has been used within an Innovate UK funded automation project. The automated tool-changer programme reached a significant implementation milestone in this period, and this is now concluding to a production ready version to be tested on a pre-production meso platform produced by Cranfield spin out **Loxham Precision Limited**.

Significant gains in assembly time of the meso platform's ultra precision motion systems were realised during this 4th year. A crucial contribution was the student project to produce a diamond fly-cutter. This has enabled the internal motion platforms to be produced much quicker and at a lower cost, with better end-product quality. See https://www.youtube.com/watch?v=ph4yYxQeltE. Some cost saving has been obtained in the assembly time, and allowed the lead-time for each machine to be reduced without an increase in required manpower or materials.

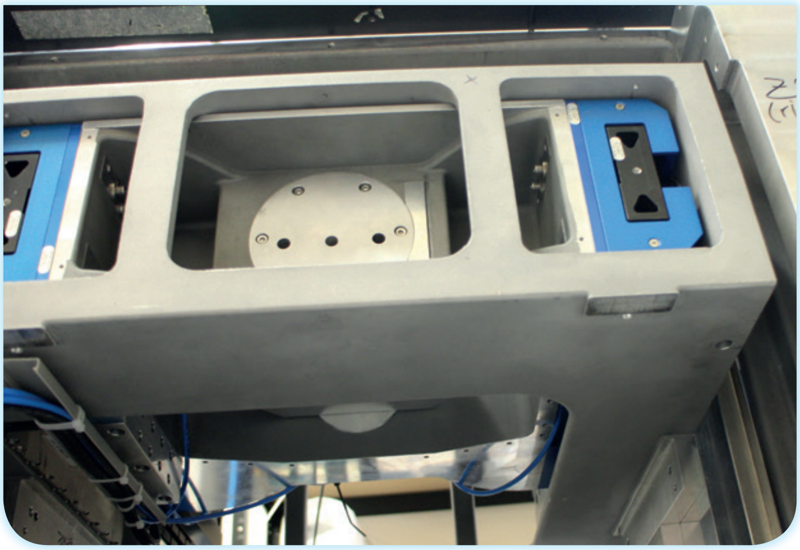
Other notable research outputs include the precision mechatronic activity being performed by PhD student Jonathan Abir. His work is sponsored by the McKeown Foundation for Precision Engineering and Nanotechnology and seeks to establish a control method entitled *virtual metrology frame*. The concept is under a patent application. In broad terms this control concept achieves a metrology frame basis using accelerometers. The control method offers a potential route to compensate for structural resonant modes of machine structures. Given validating results, the method could be applicable to a wide range of motion systems. The novelty of this control concept and the meso platform idea has been widely recognised.



Keynote presentations of the meso platform were given at the American, European and Asian International Precision and Nanotechnology Societies during 2015.

The meso-scale micro-machining centre has reached the commercialisation stage. Variants of the design concept have been made available for sale via **Loxham Precision**. Several enquiries have been received and 2 specific platform orders have been received. This research platform itself is now in the commercial domain.

It is apparent that the meso research platform has significantly influenced ultra precision machine tool manufacturers. Many of the US, Swiss and German manufacturers now claim to produce highly compact machine systems following the Centre's research direction. Whilst the meso platform programme itself has entered a commercial phase, process research using such platforms will continue to generate research outputs, from the work already conducted and planned work during the next years.



Reel to Reel Platform

The reel to reel platform is now heavily into the development and assembly stage. Detail design of all the major sub-systems were completed early in the year. High specification machine sub-systems have been created with selected UK companies. By working closely with these UK companies the Centre has already translated key research findings and future production machine system demands. Some of the more significant developments are detailed here.

The two main 20 tonne granite platform bases were delivered and numerous subsystems mounted in position as indicated in the images.

Reel to reel processing demands high accuracy smooth and stiff rotary motion systems. In order to fulfil this demand it was decided the Centre would create a unique UK based supply chain to produce ultra precision high stiffness rotary spindle axis. The key specification demands were sub micrometre accuracy of axis of rotation together with high load capacity (>250kg) and stiffness (>180 n/μm). It was also needed to produce the spindles for a cost of less than £30,000. This cost was less than 50% of the purchase price seen by US and German suppliers. An initial prototype spindle was created and performance tests revealed good basic motional accuracy but limited stiffness. A redesign of the spindles hydrostatic bearing design was performed and 6 new spindles have been manufactured and being readied for testing. The unique attribute of the design is that it employs easily machined materials whose bearing surfaces are coated using technology applied in the motor racing industry.

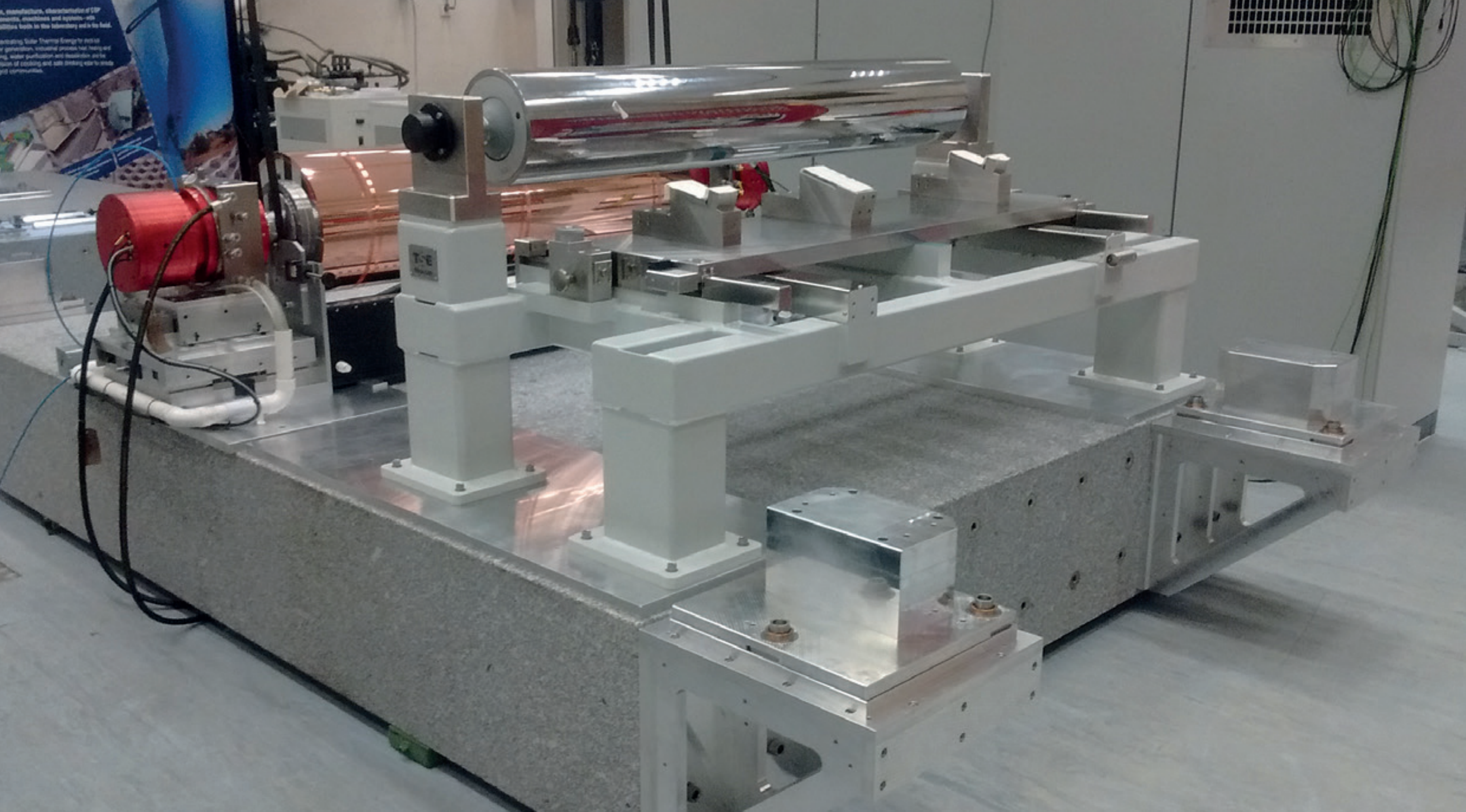
In parallel, spindle designs have been created in partnership with **NSK** (Japan) who have provided a senior researcher to work alongside the reel to reel research team providing machine design and development support. Conventional spindles will also be available to employ on the reel to reel platform as is needed.

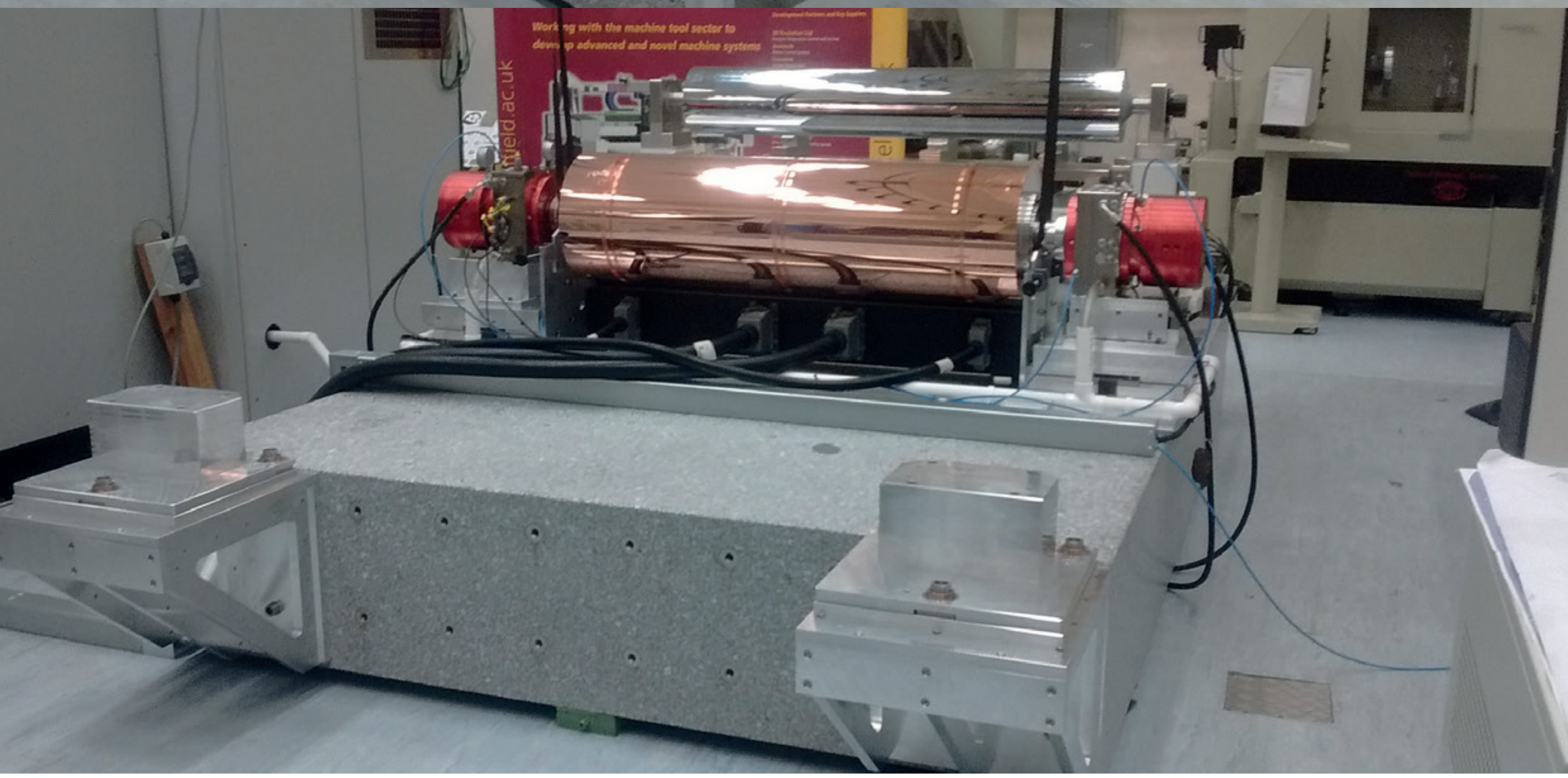
Ultra precision drum rollers have been produced by the **UPS^2** activity located in North Wales. This UK manufacturing activity stemmed from the EPSRC funded **UPS^2** Integrated Knowledge Centre. The ultra precision drums being employed within the reel to reel platform are fully manufactured in the UK. These drums require fabrication, heat treatment, machining, coating, balancing and ultra precision diamond machining. Each drum represents a major investment for a reel to reel production system and their surface quality is a critical demand. The quality of large micro-structured drums produced by **UPS^2** have been found to be a of a world leading quality. Measurements performed by the **National Physical Laboratory** (NPL) have shown embossed instrumented films offer a 100nm position measuring accuracy potential.

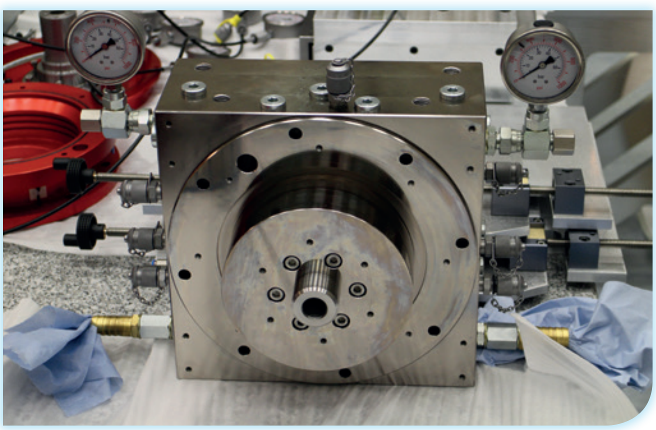
To enable a rapid production rate, a fine control method to apply thin acrylic layers (and other polymers) to the film substrate is needed. After significant investigations, performed in partnership with 2 UK SME's **Microsharp** and **iXscient**, and following a competitive tendering process, it was decided the Centre should partner with **TE Troller** of Switzerland. A high specification slot die application method was devised and procured. This polymer layer application system was delivered towards the end of 2015. In order to polymerise the applied layers after embossing it is necessary to expose the structured film to a short wavelength high intensity light. Traditional technologies using large "mercury" lamps have been found to be problematic; new UV LED type systems have been pioneered. A leading manufacturer in this emerging market in a UK SME called **UV Integration Limited**. A 20kW power 1.4 metre wide system was specified and developed by **UV Integration Limited** for the platform. This UV LED system was delivered early in 2015 and is now mounted in location within the platform. In order to employ this high power illumination system on the platform it was necessary to develop an effective temperature control unit. The Centre partnered with another UK SME, **3DE Limited**, to create a 24kW capacity high accuracy temperature control system.

Sub-systems for roll-on and roll-off and the control system motional technology have been designed, built and installed. The final commissioning of the slot die coater and the UV LED system await some final assembly. The technique to position control, the so-called "nip" roller, remains in development. In line measurement sensors have been defined and developed in partnership with the **National Physical Laboratory**.

The reel to reel platform has made significant progress over the past year. It is in the assembly and sub system commissioning stage. A number of sub-systems arrived simultaneously, all requiring some final assembly, testing and platform integration before final commissioning of the completed platform can commence (due summer 2016).







The Research Portfolio

The research portfolio is comprised of two heavily interlinked strands focused on research into Ultra Precision Processes and Ultra Precision Machines. The research topics presented here are those that are currently in progress and are considered to be of significant importance to the development of next generation ultra precision processes and products.

These projects are delivered by both Cambridge and Cranfield students and researchers at other UK universities and are often directly related to the interests of the Centre's industrial collaborators. The research portfolio is kept under constant review and subject to periodic justification of the allocated resources.

An Inkjet/Ultrafast Laser Hybrid for Digital Fabrication of Biomedical Sensors

Yoanna Shams | **Email:** ys420@cam.ac.uk | **Sponsor:** M-Solv Ltd

New digital technologies are needed to complement lithography for low volume manufacturing of personalised biosensors and companion diagnostics. These new technologies will enable ultra-precise patterning of advanced functional materials that are often sensitive to the lithographic process, while also minimizing expensive biological and nanomaterial waste.

The focus of the PhD research is to develop a novel manufacturing method for high resolution digital patterning of functional materials for niche, low volume applications such as sensors and responsive devices. The underlying techniques include:

Inkjet Printing:

a. Biological elements
b. Advanced functional materials for sensing and
c. Catalysts for nanomaterial growth

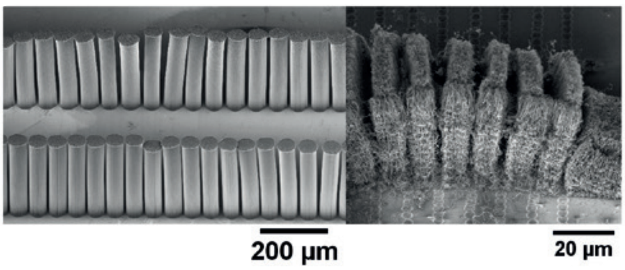
Ultrafast Laser Ablation:

a. Accurate structuring of sensing elements to sub-micron resolution
b. Controlling the surface chemistry and delivering quantitative sensing

The three key developments since the last report are listed below:

i) A detailed literature review was conducted on the key technologies in biosensing and emerging technologies in nanofabrication and production of sub-micron scale biosensing platforms. This was part of the first year report and was also a separate deliverable for the industrial partner, MSolv Ltd.
ii) A first year report was submitted and examined.
iii) Earlier work examined growing carbon nanotube forests from standard evaporated films of catalyst. Recent work has developed this for inkjet printed catalyst. Carbon nanotube forest growth was analysed with variations in ink concentration (and hence surface tension, viscosity) and droplet spacing. This shows a range of growth behaviours linked to the drying patterns and has been analysed with Raman spectroscopy, optical interferometry and electron microscopy.
iv) Leading on from earlier work ablating standard catalyst films, recent work examined ablation of the printed catalyst to pattern inkjet printed structures. This shows a sensitivity to laser power that shifts between improving growth in exposed areas and stopping growth completely, which needs to be followed up in later work. Biological molecules will also be targeted for the next stage of work, in place of the catalyst, to help with the fabrication of biosensors.

The project has built collaborations between **M-Solv Ltd.**, the **Cambridge Analytical Biotechnology Laboratory** and the **Centre of Science Technology and Innovation Policy**.



Inkjet printing and laser patterning of iron oxide nanoparticle catalyst for the controlled growth of CNT forests

Spatial Light Modulators and its Application in Computer Generated Holograms

Xin Chang | **Email:** xc276@cam.ac.uk

This project is aiming to lay a foundation of knowledge regarding computer generated holograms (CGH) and potential improvement to upgrade the quality of the reconstructed image. The most significant part of this project is the algorithm to compute the hologram with a satisfactory image quality and computation speed. Various algorithms were examined including Gerchberg–Saxton algorithm, Fienup algorithm and Fidoc algorithm. The Gerchberg–Saxton algorithm is essentially an iterative method, which is capable of converging the error between the target image and the reconstructed image. Weight is introduced into the calculation in the Fienup algorithm which makes the convergence faster. Further improvement is also achieved with the Fidoc algorithm by implementing a 'don't care' area, where the generated noise is disposed.

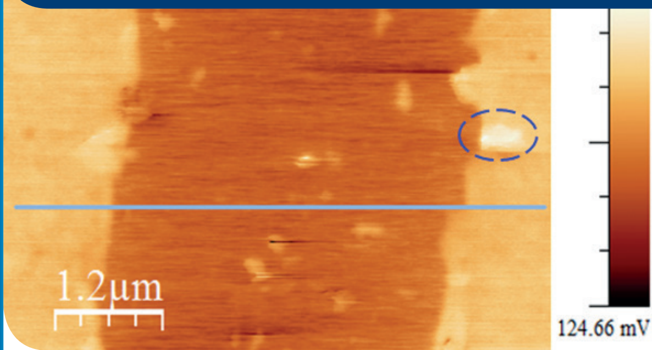
In order to compare these algorithms, several criteria are also used such as the amplitude of the reconstructed image and the rate of convergence. In the end, an optical system was setup with the help of Dr Zhengxi Chen, to implement the reconstruction process. The hologram is loaded upon a liquid on crystal silicon (LCOS) device and the image is printed on a diffuser.

In order to assess the image quality directly, other criteria are employed such as the structural similarity index (SSIM) and signal to noise ratio (SNR). Further improvement is pointed out in the end such as using a filter to eliminate the DC term. This project is a good combination of theoretical study, simulation and practical experiment and it is of great importance to further study in this field.

The reconstructed image with a DC term

Evaluating Femtosecond Laser Ablation of Graphene on SiO_2/Si Substrate

Tianqi Dong | **Email:** td307@cam.ac.uk | **Sponsor:** National University of Defence Technology



Kelvin probe force microscopy (KPFM) surface potential map of the cut kerf shown at the edge where the graphene flake has folded over itself to create a bilayer. Graphene is indicated by the dashed circle, having a higher CPD than the monolayer graphene.

Lithography is the typical method to fabricate graphene devices. This involves a long sequence of process operations and may increase the risk of contamination. Currently, research has shown the potential of femtosecond laser micromachining in fabrication of graphene devices in a maskless way, for its capability to provide free-form post-patterning, limited thermal effects, and high processing speed.

We have evaluated a femtosecond laser ablation process of graphene on SiO_2/Si substrate. In our process, the single-pulse fluence range was determined to be 66 mJ/cm^2-120 J/cm^2, in which the selective removal of graphene was achieved without damaging the silicon substrate. SEM images revealed high quality cuts (standard deviation 40 nm) with little damage and re-deposition. Raman maps showed no discernible laser induced damage in the graphene close to the ablation zone. Atomic force microscopy (AFM) revealed an edge step height ranging from less than 2 nm to 10 nm, suggesting little removal of SiO_2 and no damage to the silicon (the central path showing sub ablation threshold swelling). This could because the absorption of Si is higher than graphene though below their damage threshold at near infrared.

The effect of the ultrafast laser on the surface potential at the cut edge has been measured. Subthreshold process can induce defects in graphene and the defects were analyzed by Raman. This could provide a new way to functionalise graphene for biosensor applications.

Precision Glass Microstructuring Using Femtosecond Laser Induced Chemical Etching

Wenhe Feng | **Email:** wf230@cam.ac.uk | **Sponsor:** Amplitude Systèmes

A prototype fluidic chip was designed and made with femtosecond laser induced chemical etching (FLICE) to which commercial microfluidic tubing systems could be connected. Densified suspensions containing M. luteus and E. coli were injected into the chip for Raman spectroscopy detection, and their respective characteristic peaks were successfully measured. This part of the project was undertaken in collaboration with **Hydrolight**, Cork and **Cork Institute of Technology**.

Investigation of laser affect zones was conducted utilising variable pressure (VP) SEM and Raman spectroscopy. The VP-SEM confirmed the existence of nano-porosity contained within the laser affected zone, and Raman spectra of the LAZs revealed an increase of less-membered rings in the silica network, which enhanced the KOH etch rate. Strong fluorescence in over-exposed LAZs indicated the existence of defects induced by a thermal process that was not in favour of enhancement of the etchability.

Finite element method was used to simulate the evolution of the tunnel's geometry during the selective etching process. The influence of the models dimensions, selective chemical reaction rates, diffusion and mass transfer equations was investigated in 2D domains and a time-dependent analysis was conducted, leading to a simulation result in good agreement of experimental data.

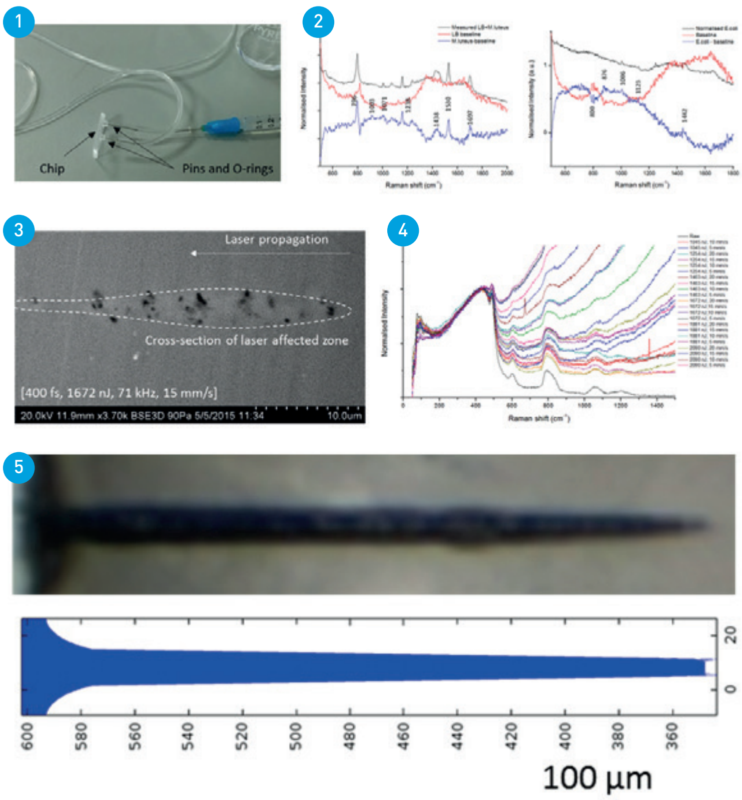


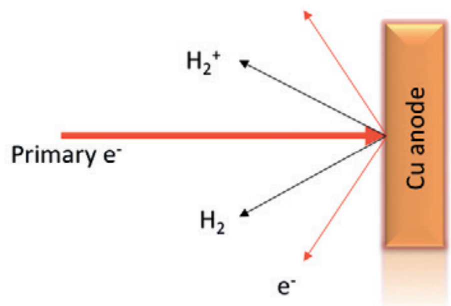
Figure 1: A chip with push-fit microfluidic tubings connected to the receptors Figure 2: Raman spectra (blue) of *M.luteus* and *E. coli* dense suspensions Figure 3: The VP-SEM image of a laser-written line's cross-section after etching for 1 min Figure 4: The Raman spectra of unprocessed glass and laser processed lines from 0 to 1500cm^{-1} normalised at 435 cm^{-1} Figure 5: A comparison of the microscope image of the tunnel etched using KOH solution at 120°C for 1 hour and FEM simulation result.

Anode Materials for High Power Microwave Devices

Daniel Gortat | **Email:** dg458@cam.ac.uk

Recent advancements in field emitters for High Power Microwave (HPM) devices are towards new materials for cathodes and anodes. While the investigations of cathodes appear to have reached a high level of success, the anode area still remains underdeveloped. Present anode materials limit the lowest achievable pressure in an HPM device, thus reducing its efficiency. The challenges lie with the anode's significant contribution to outgassing and plasma formation, caused by its secondary electron emission, all of which are thermally driven phenomena generated by the electron beam impacting the anode's surface.

The goal is to eliminate these products and thus increase the HPM's efficiency by investigating materials which would most benefit anode applications, as well as finding optimal outgassing and secondary electron emission reduction methods and applying them to the selected material choices.



Optimising the Performance of Fibre Optic Sensors using Holography

Jaliya Senanayake | **Email:** sjs216@cam.ac.uk | **Sponsor:** Michell Instruments

In this research we investigate the dependence of fibre optic sensor performance on the mode decomposition of light within the fibre. The aim is to explore if, for any given sensor, particular fibre modes contribute to sensing more than others, and if so, how this may be used to improve the performance of the sensor.

As demonstrated previously, a Holographic Launch Scheme is used to excite specific modes of the fibre. More recently, the hologram generation scheme is scrutinized to examine the limitations it poses when launching into heavily multi-mode fibres. The investigation reveals how changing the accepted minimum efficiency of the hologram, the Gaussian illumination beam width on the SLM, and cooling profile of the Simulated Annealing algorithm affect the subsequent quality of the hologram replay fields. This information is then fed back into the hologram generation algorithm, so that for each target mode, the algorithm chooses the cooling schedule parameters that yield the best possible replay quality. Furthermore, a fundamental limit, the bandwidth of the hologram, is identified. This limits the detail achievable in the replay field, and can only be surpassed by altering the optics of the system.

With recent work in sensing, a polymer layer is formed on the surface of the depressed fibre cladding. The polymer, which may be functionalised for different analytes, swells in the presence of the analyte thereby altering the fibre transmission. The polymer layer is formed by curing the monomer solution with UV light passing through the fibre. Thus curing occurs via the evanescent field, yielding thin layers which increase sensitivity.

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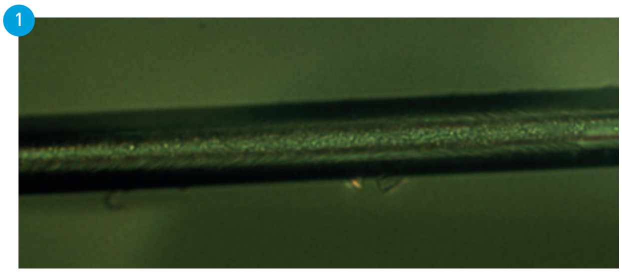

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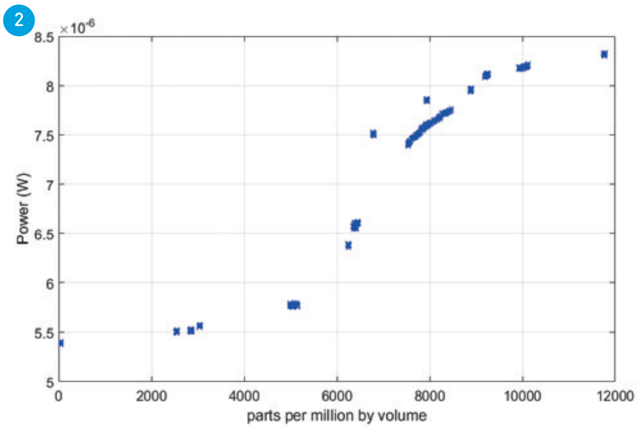


Figure 1: Poly(HEMA) formed on the surface of a side polished fibre. Viewed under a microscope, the polymer layer appears as surface roughness Figure 2: Polymer coated fibre demonstrated for vapour phase humidity sensing.

Figure A shows a poly-HEMA layer formed on the surface of a side polished fibre. pH sensing is demonstrated using this polymer coated fibre, and the wavelength response considered. Vapour phase humidity sensing is also attempted using this polymer (see Figure B). Although the response time (based on diffusion) is slow, it does have a sharp response with dew point temperature.

Ultra Precision Control of a Reel to Reel Process

Andrew Graham | **Email:** a.r.graham@cranfield.ac.uk

While reel to reel manufacturing has been used on an industrial scale for many years, recent research has been conducted in developing its future application in the production of electronics. Conceivable products include photovoltaic plastics, wearable technology, and flexible screens, all benefitting from the lower prices made possible by the use of a reel to reel process.

The motivation for this project is to develop a next-generation, UK-based manufacturing capability in reel to reel processing.

Before this can be achieved, advances are required in three areas: control of the web, measurement of the features printed on the web, and flexible, semi-conducting materials. This project will focus on the first two of these requirements, its aim being to design the control and metrology systems for an ultra-high precision reel to reel process capable of achieving one micron feature accuracy during the printing process.

Design, Fabrication and Characterisation of Hierarchical Branching Vascular Networks

Dulce Augilar-Garza | **Email:** dma38@cam.ac.uk

Development of engineered artificial tissue has an enormous life-saving potential through the generation of artificial organs for implantation and other research purposes. Currently, the main challenge in tissue engineering is the vascularization of tissue. There is a requirement for human-body-vessel-resembling blood vessel networks that will ensure the proper perfusion to all cells within the living tissue. Inkjet 3D printing is a versatile method for the fabrication of such network structures, as it allows reproducibility of the vascular structures as well as compatibility with the materials chosen for this purpose.

This PhD project is a continuation of the long project that was undertaken during the MRes year, under the supervision of Dr. Athina Markaki from the Materials Engineering & Material-Tissue Interactions (MEMTI) group at the Department of Engineering, University of Cambridge.

The main aim is to design, fabricate and characterise branching vascular networks that resemble those of the human body, within hydrogel materials. This includes three main stages: the construction of a vascular network in a 3D CAD software with help of the appropriate algorithms ensuring the fulfilment of physiologic laws, the exploration of available methods of fabrication for these structures in hydrogels, and characterization of the network structures. A secondary, but equally important aim is to characterise and understand the flow within the vascular channels, and the effects it has on the cellular walls.

During the long project, an algorithm for the generation of vascular tree structures was programmed in a CAD software, compatible with an inkjet 3D printer. At the current stage, the algorithm is being optimized to produce functional and perfusable vascular network structures.

Control of Residual Stress and Failure Mechanisms for CS and LCS

Laurent Michaux | **Email:** lm586@cam.ac.uk

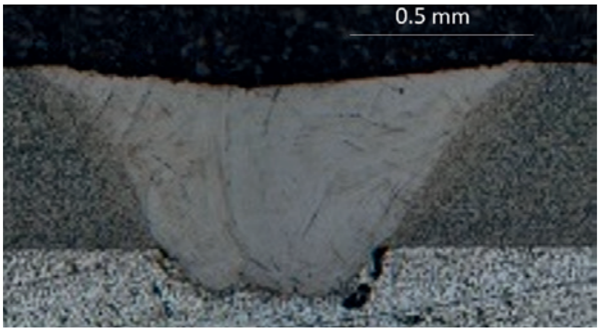
Work was undertaken to investigate a technique using a high energy pulsed laser to induce changes in metallic coatings through the laser-material interaction. The LaserForge™ process was identified as a suitable candidate for investigation. Work was done to understand the laser-material interaction required using a high energy pulsed laser, experimental parameters were identified and it was found that a melt based process was required.

A theoretical review of the key parameters affecting the performance of coating deposition was done. Stress was identified as having a significant impact on the deposited coating and an area which requires greater control. The coating through thickness stress profile can be affected by variables such as material choice, surface preparation and deposition methods. The magnitude of the resultant stress has a significant impact on the deformation and delamination of the coating. This can reduce the lifetime of the coating leading to early failure.

The current focus of the project is building on the existing work and understanding to control the residual stresses and failure mechanisms of the metallic coatings, in cold spray and laser cold spray.

The issue of stress will be addressed by understanding and modifying the stresses in the coating using a laser to control heat to the surface in order to induce the desired final stress in the coating. This process can be done in or post process. Higher quality coatings with greater control will therefore be possible.

The failure mechanisms of deposited metallic coatings are also being investigated with the aim of increasing deposited coating resistance to delamination and complete failure. This will increase the lifetime and performance of the coating under demanding applications.



Cross section of three lines of adjacent layer pulses used to bond Ti 6-4 (top) onto an aluminium substrate (0.8 mm spot, 6 ms, 1400 W).

Laser Processing of Carbon Nanotube (CNT) Fibres and Films

Francisco Orozco | **Email:** pfo21@cam.ac.uk |
Sponsor: Air Force Office of Scientific Research (USAF)

This project aims to develop a repeatable and reliable customized field emission device (FED) with an emission of more than 10 mA to be applied as sources of high power microwaves in the Air Force Research Laboratory (AFRL), Directed Energy Directorate. Previously we reported that advancements have been made on production of FED and ease of handling techniques of CNT material.

Up to date results show the coating process delivers an improvement of emission of 18% compared to unprocessed material. After these results work has started on the following points:

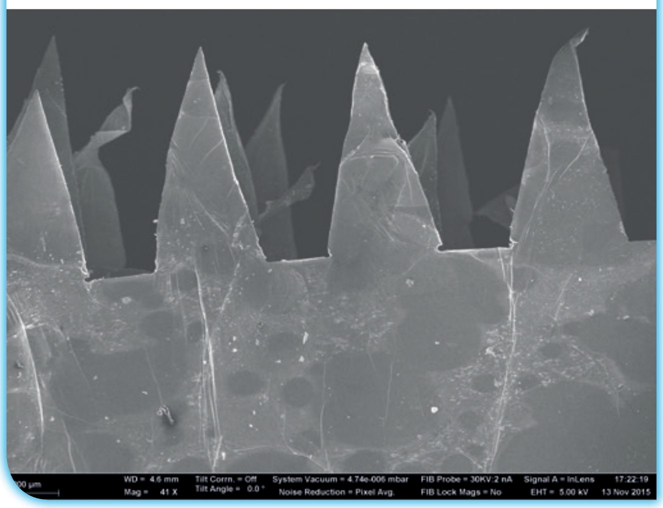
Design of process for cathode fabrication

A new process has been developed for the production of these cathodes. The process is: Step 1: Coating to handle the material and improve the emission. Step 2: Laser cutting to desired geometry and dimensions. Step 3: Array alignment and bonding. Step 4: Mounting to copper slabs for field emission testing.

Scalable production route for fibre arrays

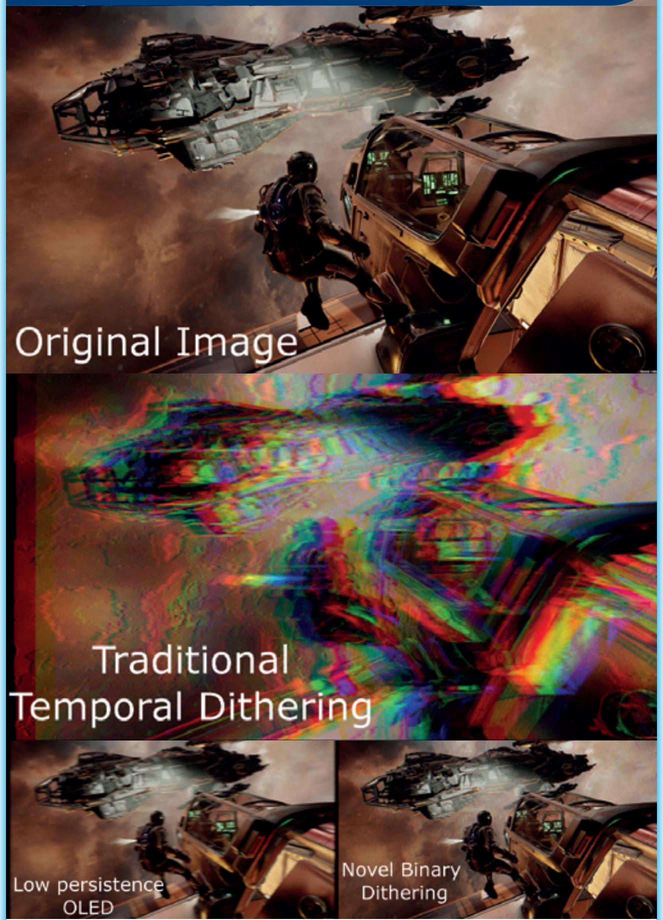
Arrays can be reproduced in a repeatable manner using commercially available technology which can be scaled up with relative ease. Arrays have been made using fibres and films. Figure 1 shows an array that was built stacking 3 films using the production process developed. These arrays can be manufactured having repeatable alignment and can have customized geometries. Latest samples made had 8 films stacked giving 48 emission tips. Field emission testing of these will be made in the following 4 months to ensure device reliability.

Figure 1: Sample trial of 3 film stacked array made with the process developed. Image seen here shows some tips being bent due to material being damaged by sample transportation.



Display Motion Error Reduction through Novel Binary Dithering Schemes

George Meakin | **Email:** gm466@cam.ac.uk



Continuing the investigation into the limitations of high speed binary displays, the current focus of this project is verifying the theoretical predictions of display performance using a highly flexible development focused digital projector, in a series of experiments throughout 2016.

In previous months, the computer based performance simulation has been expanded to provide images that accurately show the displacement, blur and colour breakup resulting from different schemes and rates of retinal motion. These motion-based display errors are crucial for Virtual Reality (VR) and Augmented Reality (AR) applications, and are far less severe for some candidate schemes than current technologies, making binary dithering an attractive option for the future of VR.

The accompanying image shows the difference in visible detail for different types of display under moderate motion rates. In the medium term, this binary dithering approach can be extended to Ferroelectric LCD for use in monitors and mobile displays where the higher refresh rate, resolution and lighting efficiency will allow FLCD to greatly outperform other LCD types.

Precision Fibre Optic Carbon Dioxide Sensor

James Barrington | **Email:** j.h.barrington@cranfield.ac.uk

This PhD project, based at Cranfield University within the Engineering Photonics Centre, is focussed on fabricating a precision engineered carbon dioxide sensor for environmental and healthcare monitoring. The ever increasing desire for portable sensing devices has led to the requirement that sensing elements must be able to deliver high levels of accuracy and sensitivity yet possess micro-scale dimensions. Interestingly, the rapid development of optical fibre technology in recent years may provide the solution to this problem. Provisionally, this research will be based on optical fibre modulation through the utilisation of long period fibre gratings. These micro gratings allow the light transmitted in the fibre's core to interact with the surrounding environment thus providing sensing capabilities. To further enhance the precision of the sensor, the application of a carbon dioxide sensitive coating will be applied to the cladding of the modulated optical fibre. It is anticipated that this device will be integrated with additional fibre sensors to provide a single multi-variant sensing platform.

Precision Metrology for Large Freeform Non-Specular Surfaces

James Norman | **Email:** j.p.norman@cranfield.ac.uk | **Sponsor:** Hexagon Metrology

This project aims to build a system that will enable low uncertainty measurement of metre-scale non-specular freeform surfaces. As such, a literature review has been undertaken to determine the sources of error that contribute to the uncertainty of the current state-of-the-art large systems capable of measuring this type of surface. The review has identified two significant error sources for current measurement systems; the largest source of error is due to the high uncertainty in the positioning of measurement probes; another source is the measurement uncertainty in the probes themselves.

The current strategy for measuring non-specular metre-scale surfaces – for instance segmented freeform optics post-grinding – in the mid- to low-spatial frequency bandwidths (S-filter), involves the use of contact probe based systems where measurement precision is a limiting factor. State-of-the-art contact probes have a measurement uncertainty due to errors including: the probe-surface interface position, flexibility in the probe, and thermal expansion of the probe, among others. Equivalent non-contact optical probes claim accuracies up to an order of magnitude higher; employing these probes could therefore improve current measurement systems. In order to use non-contact optical probes to measure metre-scale surfaces, measurement stability and accuracy should be assessed.

Two experimental methods have been designed. Stability will be evaluated by measuring at a constant position for 10 hours. The position of the probe is maintained throughout the measurement period using a probe stand constructed using a low thermal expansion material. Accuracy, resolution, and repeatability will be determined whilst using several artefacts with different surface roughness and measuring temperature, and humidity. The influence of roughness, temperature, humidity, and axial velocity upon the measurement accuracy, resolution, and repeatability will be assessed.

High Power Laser System with Built-In Dynamic Beam Shaping Capabilities

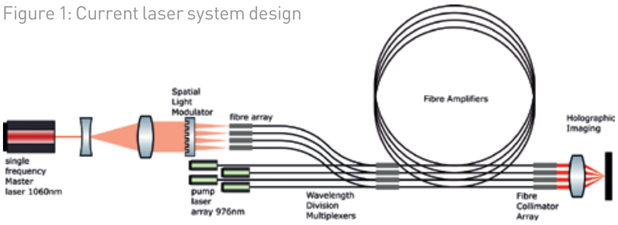
Jiho Han | **Email:** jh607@cam.ac.uk

Previously, we had proposed a concept for a high power laser system with built-in dynamic beam shaping. The envisaged principle of operation was to spatially modulate the phase profile of a reasonably low power beam using a conventional method, and then optically amplify it.

A number of designs have been investigated; the first design incorporated a high power self-imaging ring cavity as the image amplifier. These cavities would allow any transverse mode at a given laser wavelength, and hence when a pre-shaped signal is injected, it would reproduce the signal at a much higher power level. This kind of arrangement is called phase locking; it has been demonstrated many decades ago for single mode lasers. However, we have concluded that this cannot be extended to multimode lasers. Phase locking requires precisely matching the longitudinal and transverse mode, and for a multimode laser, predicting, let alone controlling these is almost impossible.

The next design attempted to use a bundle of single mode slave lasers which amplify different parts of the beam separately. Though this is technically possible, and around 3 such lasers were seen to lock onto a single source concurrently, in practice, each laser would require individual nano-meter resolution laser cavity length control to match the modes. This is now considered impractical.

Figure 1: Current laser system design



The third and currently pursued design is shown in Figure 1. The spatial light modulator couples light into a grid of fibre optics as well as modulating the phase. Each input to the grid is amplified separately through a high power fibre amplifier, the output of which are also arranged in a grid to allow for coherent interference. Similar arrangements are often referred to as coherent beam combining, but the conventional focus is on obtaining a single high brightness source. We suggest that if it can be scaled up, it would also be fit for our purpose.

High Speed Mask-Less Laser Controlled Micro Additive Manufacture

Jyi Sheuan Ten | **Email:** jst44@cam.ac.uk | **Sponsor:** Agency for Science, Technology and Research Singapore

Background

In this study, laser chemical vapour deposition (LCVD) is explored as a method for the deposition of conductive metal tracks via thermal dissociation of metal organic precursor gases at locations defined by a laser spot. This allows for a rapid and mask-less deposition technique when compared to electron and focused ion beam deposition and lithography methods commonly applied for the deposition of metal contacts to micro electronic devices. Lithography involves the use of chemical masks that may contaminate the substrate and may be an issue for building contacts to sensitive materials like graphene and organic materials. EFIB deposition techniques do not require masks but the deposition rate is very slow. This study aims to explore LCVD as a platform for the fabrication of prototypes. The study started with understanding the fundamental capabilities of LCVD and building a LCVD platform. For application areas, the LCVD platform will be used to build conductive tracks to novel carbon-based materials. Once the capabilities of the platform are demonstrated, it will be integrated with other technologies being developed in the Centre of Innovative Manufacturing in Ultra Precision.

Progress

A deposition platform has been assembled consisting of a tungsten hexacarbonyl precursor delivery system,

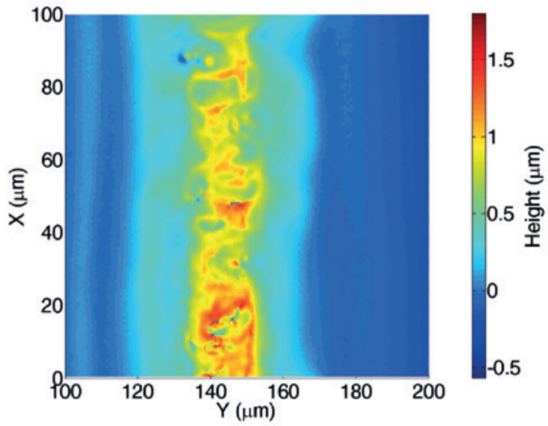


Figure 1: White light interferometry measurement of the tungsten track on SiO_2 coated wafer

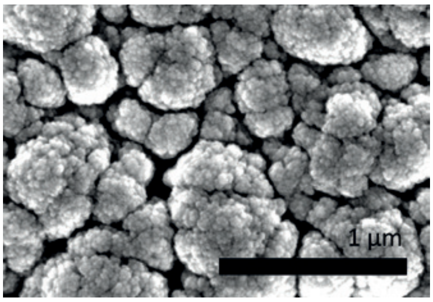


Figure 2: High resolution SEM image of deposited tungsten track on SiO_2 substrate.

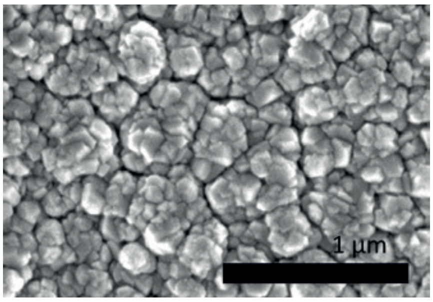


Figure 3: High resolution SEM image of annealed tungsten track on SiO_2 substrate.

a vacuum chamber with a laser window, and a 1064 nm continuous wave laser with a 40 µm spot. Using this system, tungsten has been deposited in a free form pattern, defined by the laser on silicon wafers with a 285 nm of oxide. The cross section of a line deposit as measured by white light interferometry has a height of around 1 µm with a cross section area of around 30 µm^2 (Figure 1). The highest deposition line scan achieved on the silicon oxide wafer is 10 µm/s with the potential to be increased to 2 mm/s. Energy dispersive X-ray spectroscopy confirms a tungsten composition of 73%. Scanning electron microscope (SEM) images show a columnar growth structure (Figure 2) that becomes more continuous after annealing (Figure 3). The deposition temperature is measured using an infrared thermal camera to be around 200 °C.

Control System for Ultra Precision Processing

Karen Yu | **Email:** xzjy2@cam.ac.uk

High precision manufacturing of nano- and micro-sized objects has become increasingly prominent given current technological trends. While traditional macro-manufacturing systems rely on automatic feedback loops to detect errors and act immediately, this is a more difficult task when scaled down to the single micron or less. Also, while FIBs can produce feature sizes down to 10s of nanometres, the processing time is very high and may require days for a single MEMs device. The goal of this project is to provide feedback and control to laser based ultra-precision (features at or below 10 µm) processing platforms as well as high throughput bulk removal for further FIB processing. This represents the first half of the laser FIB processing platform.

In the past year, the swept source optical coherence tomography (SS-OCT) inspection system has been integrated with the ultra precision machining platform for use during processing (shown in Figure 1). The initial targeted application is ultrafast processing of glass modification to change the refractive index for optical waveguides, modify the material for selective etching, and weld with various materials (glass-glass, glass-metal, etc.). In all these cases, the position of the modification is important and well suited for OCT based control. Figure 2 shows preliminary results comparing OCT to microscopy data, showing good agreement. Note that OCT measures optical path length, requiring the index of the material to calculate the physical path difference.

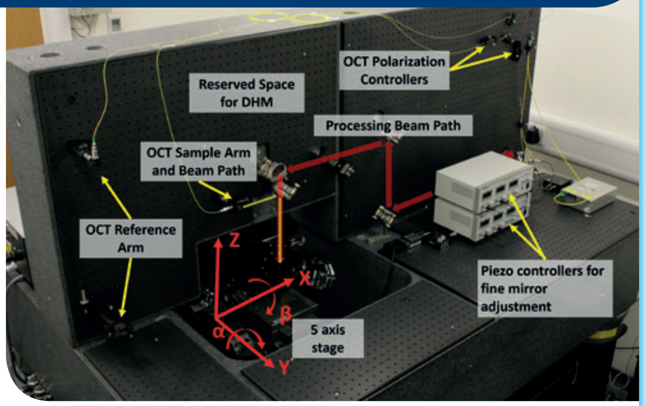


Figure 1: OCT integrated with ultra precision machining platform

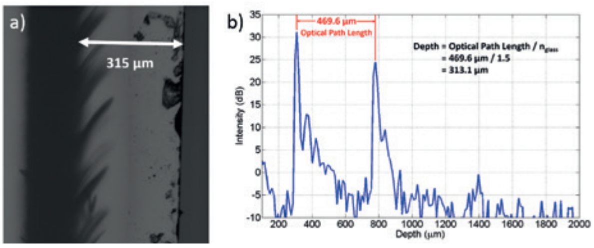


Figure 2: Shows (A) optical microscopy profile of modification in glass and (B) OCT measurement of modification.

The next step for the project is to continue with analysis of glass modification, specifically welding, where OCT will be used to a) control the depth at which the weld occurs, and b) control the processing parameters to create consistent welds.

Jaguar Land Rover iHUD Project

Matthew Pryn | **Email:** mp550@cam.ac.uk | **Sponsor:** Jaguar Land Rover

This project aims to develop a 3D heads-up display (HUD) to enable immersive augmented reality for commercial automotive markets. The display will be full colour, high resolution, able to display at least 10m of depth, and with a wide field of view for immersive and natural information display. The display must be visible at night in dim ambient light, and also in bright sunlight, and must be compatible with polarised sunglasses. The 3D aspect of the HUD enables a more intuitive way to visualise information, allowing drivers to better understand the distances involved.

The HUD will be used to enhance road safety by highlighting hazards,such as the edge of the road in low visibility conditions, nearby cyclists and pedestrians, and a marker at the current braking distance for fast traffic flow. The HUD may also be used for navigation with route arrow overlays on the road, callouts indicating petrol stations, magnified road signs for easy reading, and ghost car display for navigating complex junctions.

Current HUD solutions are projection based, requiring relatively large and bulky optics, which is challenging to scale efficiently to a large area 3D display. An alternative approach utilising compact waveguides is being investigated for this project. Light from arrays of LEDs is coupled into the windscreen using total internal reflection.

A built-in transparent film of diffracting gratings couples light from the windscreen to the user along specific rays. The film is electrically switched to control pixels individually, and light intensity is adjusted by modulating the LED array. The control over both the direction and position of the emitted rays allows a light field image to be displayed, enabling depth perception. Unlike current 3D displays, a light field display faithfully replicates all the physiological cues required for depth perception, and so causes no eyestrain or nausea.

However, such a display requires a very high density of emitting pixels, and each pixel requires sub-micron manufacturing precision, posing a severe manufacturing challenge. Additionally, the transparent film must be flexible to conform to the curvature of the windscreen, and sufficiently robust for operation in harsh automotive environments. A number of film architectures and manufacturing solutions are being considered, including photolithography and nanoimprint lithography.

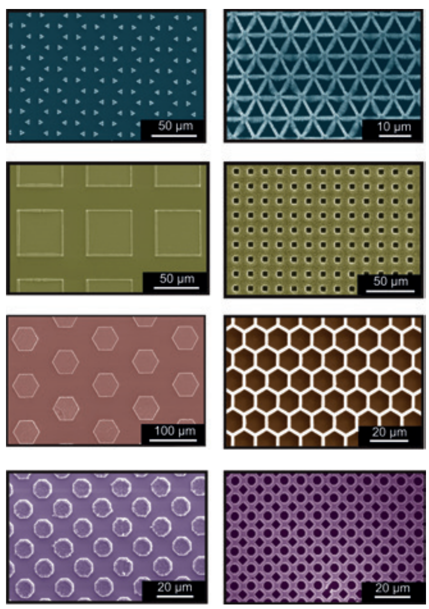
A small scale low resolution proof-of-concept is currently being designed. Larger prototypes will be developed if successful. The expected challenges for the HUD include: optical efficiency, display resolution, and the large area precision manufacturing.

Ordered Nanomaterials for Electron Field Emission

Clare Collins | **Email:** cc769@cam.ac.uk | **Sponsor:** Cambridge X-Ray Systems and Cheyney Design & Development

Clare's experimental work looks at designing and fabricating carbon nanotube (CNT) field emitters with varying morphology, in order to better understand the Fowler Nordheim equation and the local field enhancement factor, which is not well defined across the field. A number of variables include emitter height and number of edges. Theoretically, more emission should be seen when there are more edges. Measurements have begun on the 52 variations that have been fabricated so far using a custom built Scanning Anode Field Emission Microscope (SAFEM). Analysis of the data collected from the SAFEM will hopefully reveal information about the influence of emitter geometry on field emitting capability.

Clare has had an article accepted by Advanced Science. The article is a review of all the current materials that have been studied for the use in field emission to date, looking particularly into the effect of the work function on the material performance. She is also attending the MRS Conference in Boston (December 2015), presenting a poster.



Advancement of Plasma Figuring Technology to Reduce MSF Errors on Metre-Scale Optical Surfaces

Nan Yu | **Email:** n.yu@cranfield.ac.uk

This PhD project is focused on design, fabrication, and characterization of novel nozzles for Inductively Couple Plasma (ICP) torches that are used for the optical fabrication of metre scale surfaces. Three main aspects of this research work were achieved this year.

First, a CFD model based on the High Temperature Gas (HTG) was created for the current De-Laval nozzle used on the ICP torch. A comparison between the experimental material removal footprint and its counterpart predicted axial velocity profiles showed to be satisfactory. This numerical approach enabled investigation of aerodynamic behaviour of plasma jet. Moreover, the model was used to explore rapidly other nozzle designs. A set of new nozzles designed and manufactured are shown in Figure 1.

Second, the investigation of the RF network was carried out on the Plasma Delivery System (PDS) of Helios 1200 (Figure 2). The influences of three system parameters of the PDS were investigated, and an optimization was suggested. The selected electrical parameters of the PDS were load capacitance, tune capacitance, and the state of the induction coil. The results of this investigation enabled the determination of the most influencing parameters and a method for tuning the PDS.

Third, an investigation of the energy dissipation rate that best characterised the ICP torch was undertaken. Fine temperature measurements and calculations were performed to determine energy dissipation rate values. Experiments were carried out in a very challenging environment where intense electromagnetic fields dominate and perturb signals provided by temperature sensors (Figure 3). Energy dissipation rate of the ICP torch was obtained from the temperature changes of its coolants. In addition, this work enabled the derivation of energy both provided for gas heating and lost by radiations. This investigation enabled a good understanding of the plasma figuring in terms of the energy dissipation rate. Also, the plasma average temperature derived from this energy dissipation investigation was found to be in a good agreement with that calculated through the CFD model.

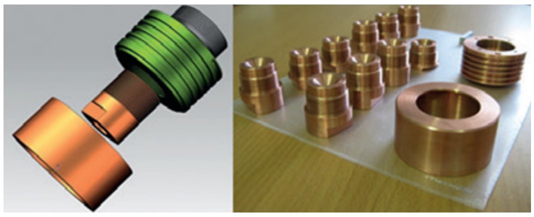


Figure 1: Designed and manufactured De-Laval nozzles with different internal dimensions

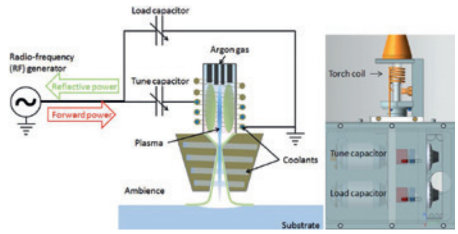


Figure 2: Schematic of the Plasma Delivery System and its CAD model

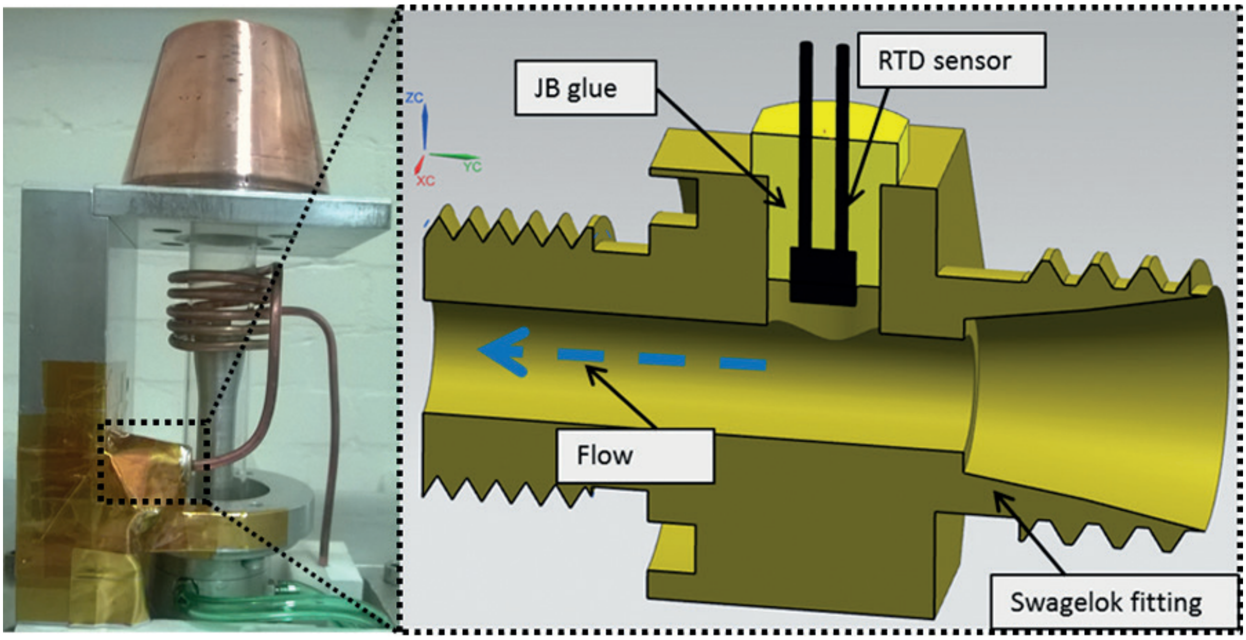


Figure 3: Shielded RTD sensor close to the RF coil (in the strong EM field)

Development of Non-Contact Methods for Measuring the Outside Geometry of AM Parts

Patrick Bointon |
Email: Patrick.Bointon@nottingham.ac.uk

Metrology is an important tool for manufacturing as it provides the necessary feedback for process control and post-process troubleshooting. Without fast and accurate metrology, setting up production procedures and maintaining production tolerances to minimise scrap parts is not possible. Metrology is especially important in the field of additive manufacturing (AM), where, in order to scale up production, multiple machines are used on the same manufacturing floor. Each machine can be considered as being an independent manufacturing process or manufacturing line that needs process feedback in order to achieve tight tolerances on the products being manufactured and allow comparability.

In order to further the metrology measurement field and aid the continued progression of additive manufacturing, a new and more flexible system needs to be developed. This is due to the limitations of current measurement systems, such as lack of flexibility, struggle to cope with high slope angles, surface reflectivity problems and time of measurement vs performance/accuracy trade-off.

Based on current research trends and recent publications, optical methods (Coded Structured Light, (CSL)) show considerable promise and so the aim of the PhD will be to develop and utilise CSL techniques in a new system for measuring the complex geometries on additive manufactured parts. This will require optical instrument research and development and an investigation of existing commercial measurement systems currently in use. Comparisons with contact techniques will be carried out. The new system will be aimed at being capable of measurement volumes of a cube of up to 750 mm sides to accuracies approaching 5 µm. A number of industrial case study components will be measured using the techniques to demonstrate their performance with different geometries, materials and surface textures.

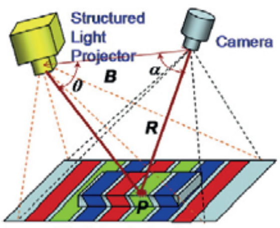
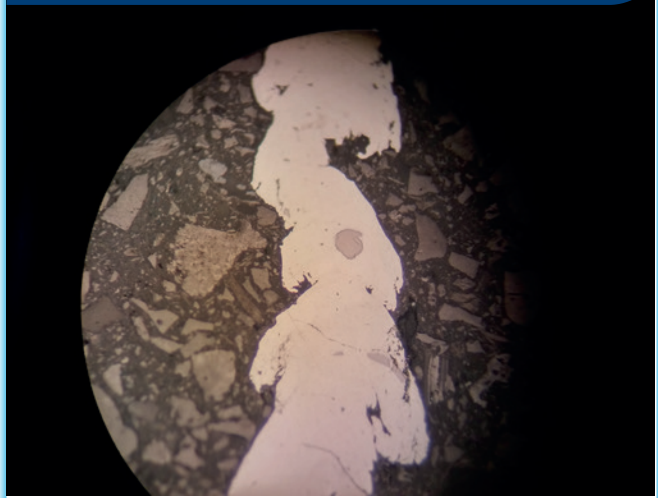


Image acknowledgement: "Structured-light 3D surface imaging: a tutorial" Jason Geng - Maryland 20852, USA (jason.geng@ieee.org), IEEE Intelligent Transportation System Society, 11001 Sugarbush Terrace, Rockville, Published March 31, 2011 (Doc. ID 134160)

Design and Development of Solid State Additive Manufacturing Techniques

Sam Brown | Email: sab200@cam.ac.uk



With increasing levels of interest and investment in metallic additive manufacturing technologies around the world, the cold spray process offers some distinctive capabilities that will offer it a unique placement within the additive manufacturing landscape. In progressing this proposed system, four key areas are being examined.

Investigation

Competitive techniques in both traditional and additive manufacturing sectors have been studied to analyse the relative strengths and weaknesses of each system. The proposed system would offer unique benefits due to the low processing temperatures, providing it with a niche advantage in some fields. Opportunities for this potential system have then been considered and classed into three categories: direct manufacturing, remanufacturing and support operations. Specific markets within these categories have been explored and quantifiable case studies are being generated.

Experimental work

The first practical challenge to be addressed in the development of a cold spray additive manufacturing system is the creation of net-shape walls. A test platform has been constructed allowing for the testing of various flow-altering techniques, to modify the deposition profile and allow net-shape creation. Methods being trialled include: hard or sacrificial backstops to spray against, profile shaping using 2D masks or stencils, and flow separation techniques.

CFD simulation

A fluid model is in development, using the ANSYS Fluent package, to increase the understanding of the flow structure around the potential substrate and backstop combinations.

The purpose of the model is to inform process parameters and highlight any issues that may arise from the proposed experimental trials, as changes to the generated shockwave due to obstacles may affect the powder deflection and velocity during deposition.

Visualisation

Investigations are ongoing for a method of observing both the gas and powder streams during deposition, allowing for verification of the CFD model and inform the choices of process parameters. One potential option is to utilise Schlieren photography of the gas jet only, allowing the visualisation of shockwaves and fluid flow in the exhaust. Particle image velocimetry would allow for the measurement of powder speeds in the exhaust, but would not provide data on the flow patterns or speed of the gas.

Ultra Precision Hybrid Laser-FIB Platform

Chris Wright | **Email:** cew53@cam.ac.uk

The aim is to produce an integrated processing route which uses ultrafast lasers and focused ion beams to increase the throughput of ultra-precision manufacturing. The main focus of this body of work is to develop the ultrafast laser machining platform into a non-contact ultra-precision machine tool, with inbuilt metrology for closed loop machining. To further the integrated processing route, a proof of concept for cross-platform processing will be carried out towards the end of the project.

A number of advancements have been made towards solutions for the ultrafast platform. These include the delivery of the platform, optical mounts, and beam diagnostic equipment. The design and manufacture of the microscope objective holder and safety enclosure is currently underway. The Talisker laser, optics, microscope and optical coherence tomography (OCT) system have been installed on the platform which has allowed for system characterisation to begin. Development has begun on the software for control of the system and has been broken down into three main components: Aerotech control, shared memory, and custom software. This arrangement allows for significant flexibility for the platform as progress is made and new systems are integrated.

The current phase of work is determining the performance of the laser and developing control strategies to stabilise the laser with respect to power, diameter and pointing stability to increase the accuracy of the ultrafast platform. This will rely on using power meters, beam profiler, motorised attenuators and beam expander to form a closed-loop control strategy. This will lead to a comparison of traditional open-loop laser machining to the implemented closed-loop control method to evaluate the performance increase.

With the laser stabilised this will lead into development of the inbuilt metrology systems for closed loop laser processing. The first stage will be to test the three different metrology systems: microscope, digital holographic microscopy (DHM) and OCT on different machined features. This will lead into a closed-loop machining process which will initially start with 2D profiles, moving on towards 2.5D manufacture finalising with a fully 3D system. Finally, a laser machined feature will be transferred from the ultrafast platform to the FIB where the feature will be aligned and milled.

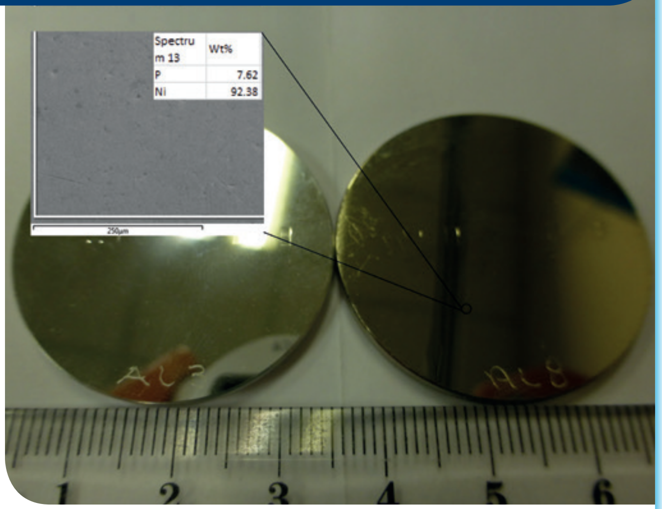
Diamond Machinable Coatings for Fluid Film Systems

Peter Xia | **Email:** p.xia@cranfield.ac.uk

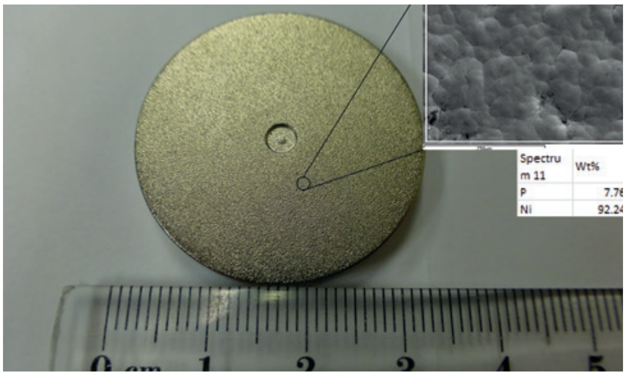
The purpose of this project is to recommend modifications and improvements (or an alternative) to the current processing route for optical quality wear resistant diamond turned coatings on ultra-precision manufactured rollers and hydrostatic bearings. In doing so, there is a need to create a common language and unified understanding of what "quality" actually means for this application between the manufacturer and consumer, in terms of the current electroless nickel plating procedure that is used to enhance the wear properties.

In the last six months, the project has concentrated on the production of a commercial production grade coating over aluminium testing coupons. As the coating thickness increases, the number of defects also increases. For diamond machinability, it is important to create coatings with 10 wt.% phosphorous content and above and to maintain the level of concentration throughout the entire deposition time. Currently, to deposit a coating of 100 µm or more thickness would require a minimum of 8 hours plating time.

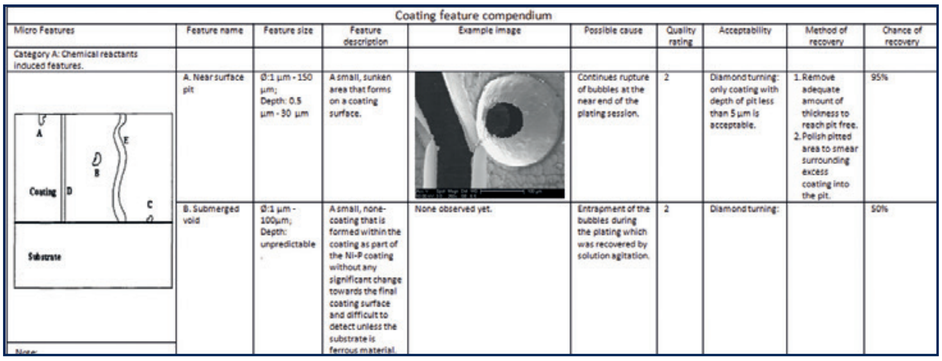
The preparation stage of the substrate prior to plating has also been investigated to identify the relationship between the starting surface finish and coating defects. It has been observed that substrate surface roughness and morphology can affect the coating finish in terms of the adhesion of the subsequent nickel coating, its smoothness and the pitting rate.



Diamond turned sample before (left, Al3) and after plating (right, Al8). The surface retains its glossy appearance with the phosphorus content at 7.62 wt.% (External plating facility no.3). Sample Al8 retains its mirror finish after plating, however the coating would be deemed unfit for diamond turning applications as the level of phosphorus content within the coating is low.



Sandblasted sample with nickel phosphorus (7.76 wt.%) alloy coating (external plating facility no.3).



Coating feature compendium

Micro Features	Feature name	Feature size	Feature description	Example image	Possible cause	Quality rating	Acceptability	Method of recovery	Chance of recovery
Category A: Chemical reactants induced features.									
	A. Near surface pit	Ø:1 µm - 150 µm; Depth: 0.5 µm - 30 µm	A small, sunken area that forms on a coating surface.		Continues rupture of bubbles at the near end of the plating session.	2	Diamond turning: only coating with depth of pit less than 5 µm is acceptable.	1. Remove adequate amount of thickness to reach pit free. 2. Polish pitted area to smear surrounding excess coating into the pit.	95%
	B. Submerged void	Ø:1 µm - 100µm; Depth: unpredictable	A small, none-coating that is formed within the coating as part of the Ni-P coating without any significant change towards the final coating surface and difficult to detect unless the substrate is ferrous material.	None observed yet.	Entrapment of the bubbles during the plating which was recovered by solution agitation.	2	Diamond turning:		50%
Note:									

Cut-out of a coating feature compendium.

Plating solutions from different sources have been used for coating quality comparison. The evidence has been gathered, with the intention of creating a surface and cross-sectional photographic compendium of all the commonly observed defects. A coating quality inspection procedure and manual based on existing ISO and ASTM standards has been drafted and currently a grading system targeting various aspects of the electroless nickel coating is being investigated.

In the next six months, the project aim is to set up a small-scale pilot scheme with an external plating firm to verify and test out the inspection system. Meanwhile, by introducing deliberate defects into the plating process, it should be possible to demonstrate the physical evidence of individual significant defects, and the effect of various defects on the diamond turning process will also be investigated.

Multiple-Beam Powder Bed Fusion Additive Manufacturing

Andy Payne | **Email:** atp34@cam.ac.uk

The focus of this research is to develop a multiple beam variant of a powder bed fusion additive manufacturing system. It is proposed that the use of multiple beam technology can lead to a reduction of thermal part stress due to de-localization of the thermal energy and an increased build rate as the system is scaled upwards.

As opposed to the conventional laser and galvo-scanning mirror technology this system will operate like a dot matrix printer; as the optical head is scanned across the powder bed individual laser diodes will be activated appropriately to create the melt pools that form the individual voxels in that particular layer slice of the 3D structure to be built.

Several scanning strategies have been formulated for the optimum movement of a multiple beam optical head over a powder bed. These scanning strategies have been tested by building single layer ribbons in free powder with a range of exposure times and powers from stainless steel 316L. For a well-balanced parameter set these single layer ribbons show very little planar distortion (0.5 mm bow over 40mm) and multiple ribbons with arbitrary shape have been successfully stitched together (Figure 1). However, despite the low distortion in single layers, the addition of multiple layers increases the thermal stresses resulting in the need for substrate anchors and full interlayer consolidation has yet to be achieved.

Currently the line building process is being analysed to identify the factors governing a stable and regular profile that is well wetted to the previous layer (Figure 2). Subsequently this knowledge will assist with the creation of thin walls, horizontal planes and the interlayer consolidation required to make good quality three dimensional parts with high density and feature resolution (Figure 3).

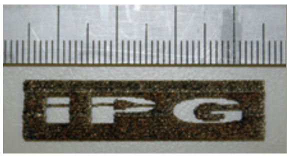


Figure 1: Single layer ribbon object of arbitrary shape

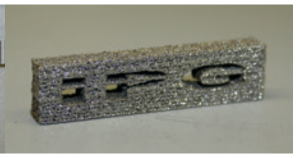


Figure 3: Ten layer prismatic object

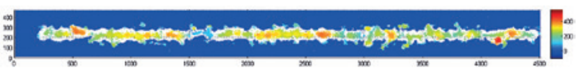
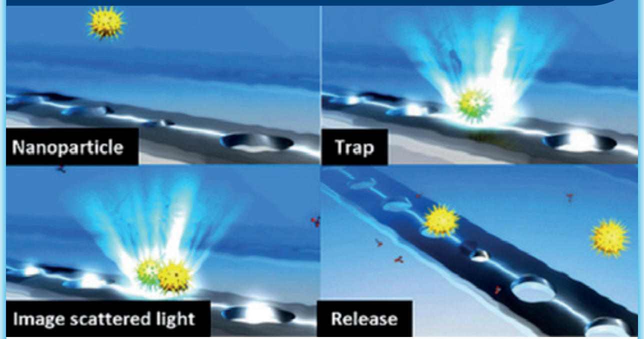


Figure 2 Height profile of a single melt line showing inhomogeneity (dimensions in microns)

Development and Optimisation of an Optofluidic Nano Tweezers System for Trapping Nanometre Crystals for Synchrotron X-Ray Diffraction Experiments

Alex Diaz | **Email:** ajd216@cam.ac.uk |
Sponsor: Diamond Light Source Ltd



With the Synchrotron community facing an increasing need to analyse ever-smaller protein crystals (particularly at the Diamond Light Source VMXm, I24 and I04 beamlines), new sample loading techniques are needed to present nano-dimensional samples to the beam for X-ray diffraction experiments.

When dimensions are in nanometres, traditional approaches, such as mounting on micro-meshes are neither feasible nor appropriate because the levels of solvent around the crystals becomes unacceptable from an X-ray signal-noise perspective, and visualization of the crystals by light microscopy becomes very challenging. These techniques, if reconfigured to work with nano dimensional samples, only offer the potential to automate. This leads to clumsy top down approaches, such as robotic handling or by injection of a crystal slurry past the detector resulting in a hit rate in the region of 10%, with the rest of the sample being wasted and requiring the imaging to take place as the sample is in motion.

One approach being given serious consideration involves optical trapping. Pioneered by Arthur Ashkin, optical tweezers apply highly focused laser beams to trap and capture microscopic artefacts ranging from a few microns to tens of nanometres, allowing for individual cells, viruses and protein molecules to be successfully manipulated. The individual specimens are transported by a microfluidics channel up to the waveguide where they are trapped and positioned into the synchrotron's beam path, as it emerges from the beamline aperture. The results of this project aim is to implement a novel bottom-up approach, to substantially increase the precision of sample loading process, improve the speed and quality of measurement and to also reduce the amount of sample wastage – all goals which will lead to a reduction analysis of cost and time.

Design and Control of a Compact Ultra Precision Machine for High Dynamic Performance

Jonathan Abir | **Email:** j.h.abir@cranfield.ac.uk

This PhD project is focused on technologies that improve dynamic position control of a compact size machine tool. The research was made by design and development of a mechatronic system, which will be implemented in the compact size machine tool – µ4 made by **Cranfield Precision Engineering Institute** and **Loxham Precision Ltd**. This research is unique and contributes to knowledge by combining the apparent antagonistic requirements of a compact size machine tool with high dynamic performances. A novel mechatronic technique – *virtual metrology frame* was developed alongside mechanical design approach, which

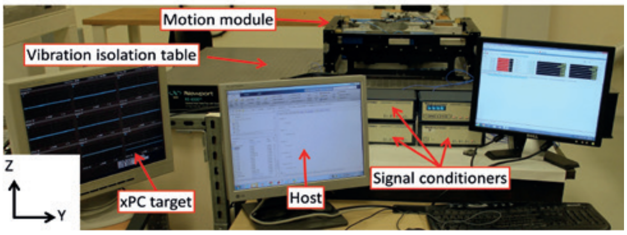


Figure 1: Overview of the novel mechatronic

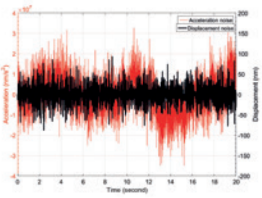


Figure 2: Displacement noise based on the long time acceleration integration

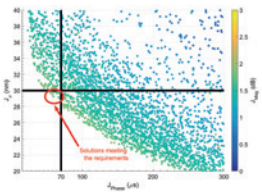


Figure 3: Pareto front graph of multi-objectives genetic algorithm optimisation of the displacement estimator

optimises the requirements of the compact size machine tool and high dynamic performances requirements.

Based on the developed *virtual metrology frame* technique, the expected machine performance is as if the machine has a metrology frame, without interfering with the size constraint. While the carriage position is measured with a linear optical encoder, a new technique for real-time measuring the frame displacement based on accelerometer sensor was developed.

Long term integration (>10 s) of acceleration signals and high accuracy acceleration based displacement sensors has been largely unsuccessful. However, in this work a mechatronic system (Figure 1) of a real-time, long term (>10 s), and accurate (σ< 30 nanometre) displacement estimator based on accelerometer was achieved (Figure 2).

The estimator is required to have low delay (J_{Phase}), low gain error (J_{Mag}), and low displacement noise (J_{σ}). Thus, a multi-objective optimization technique was used to find the optimal estimator parameters (Figure 3). A significant noise reduction on one hand and real-time estimation on the other was achieved based on the optimal estimator-filter.

In the following months, the improvement to the machine performance by the developed solution will be assessed. Then, improvements and extensions of that technique will be carried by optimising and automating the signal processing techniques alongside multiple axes demonstrator.

Novel Energy Delivery Techniques for Laser Additive Manufacturing from Metal Powders

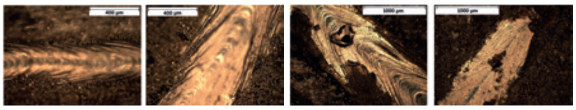
Jon Parkins | **Email:** jp623@cam.ac.uk | **Sponsor:** The Worshipful Company of Engineers

Work has continued towards improving the selective laser melting process from metal powders for medical applications by implementing a dedicated test system. Experimentation to determine the limitations of parameter space is ongoing. Beam diameters of up to 500 µm have been demonstrated to create well-defined scan tracks. Above this size the smoothness of the track edges degrades. The local energy density at the beam centre causes vaporisation at 1 kW before the edges fully melt into a smooth track. The cause is the low thermal conductivity of the stainless steel powder. It appears 1 kW is approaching a fundamental limitation of the existing regime.

The thermal gradients in the system have been identified as the key cause of melt dynamic issues and residual stresses. Thermal gradients in the melt pool cause surface tension variations which lead to melt instability. The thermal gradient between the heat source and the cooler surroundings lead to residual stress development in finished parts due to thermally-driven shrinkage. For this reason the delocalisation of heat is being considered as an important driver in improving the process. It is expected that higher scan speeds will distribute the temperature across a larger area with time and thus delocalise the energy. The scan speed limitations will be determined in the coming months.

Absolute delocalisation of heat is being investigated. This approach is employed in electron beam melting, in which a defocussed electron beam is used to preheat and sinter the powder. We propose a delocalised heating process to reduce thermal gradients and also

reduce the energy required to melt. Flash lamps and defocussed laser heating have been used to increase the temperature
of a 50 µm powder layer to 400 °C, which will reduce stresses but avoid sintering. The effects of a delocalised heat source on the melting process and on final parts are being investigated.



Top down views of laser melted tracks on substrates created with large beam diameters. Beam diameters (clockwise from top left): 400 µm, 525 µm, 750 µm, 1000 µm. Adhesion and edge quality degrade above 525 µm.

Development of Camera-Based Systems for Micro-Coordinate Metrology

Danny Sims-Waterhouse
| **Email:** epxds1@nottingham.ac.uk

Manufacturing components with micro or nano-scale features is quickly becoming a mainstream application of engineering. Currently contact based measurement systems are mainly used, but lack the speed required for manufacturing on any reasonable scale. Therefore, we must look to optical techniques to provide the speed and accuracy needed for the next generation of manufacturing metrology.

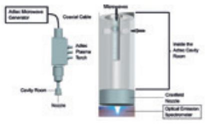
The project will centre on developing new camera-based 3D measurement systems for high-precision coordinate metrology.

Special focus will be placed on the ability to measure features with high slope angles and high aspect ratios, often outside the aperture range of the optics.

Techniques to be considered include photogrammetry and fringe projection, including hybrid designs. A number of case study components will be measured using the techniques to demonstrate their performance with different geometries, materials and surface textures.

Microwave Generated Plasma Figuring for Ultra Precision Engineering of Optics for Aerospace and Defence

Adam Bennett | **Email:** a.d.bennett@cranfield.ac.uk
| **Sponsor:** Gooch & Housego



An exhaustive and comprehensive literature review has been conducted on the different aspects of microwave plasma torch designs. Theory detailing how the microwaves are generated, propagate through air, interact with gas atoms and create plasma is available in this report. Different torch designs are grouped together according to forwarded power operation, the type of plasma generated and industrial applications.

Examples of microwave plasma characterisation by Optical Emission Spectroscopy is sourced from literature and used as a support to validate the experimental results obtained through the Adtec microwave plasma torch.

The Adtec torch was tested under a rigorous design of experiment procedure. The main torch parameters - microwave power, gas flow rate, type of gas, quartz tube design, and nozzle design - were systematically altered and their respective effects on the emission spectra of the plasma discharge were recorded. Mapped displays of the 14 areas of interest were chosen and presented.

Literature states that helium has a higher thermal conductivity compared to argon. This will yield a plasma plume diameter that is smaller and therefore a smaller tool function width. Plasma inhomogeneity varies inversely proportionally to the thermal conductivity of the gas. Hence if helium is employed as a carrier gas, compared to heavier elements such as argon, then highly stable plasma may be maintained for long periods of time.

This gas characteristic concurs with the experimental observations. The 3D maps of the helium plasma discharges exhibit lower power densities relative to that of the argon plasma discharges and the distribution of the thermal energy within the helium plasmas was more uniform than that of the argon plasmas where the energy was more concentrated in the centre of the plasma plume.

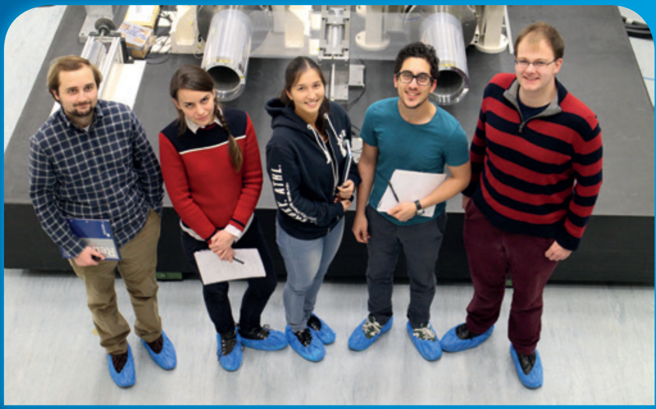
Centre for Doctoral Training

The Centre for Doctoral Training in Ultra Precision (CDT-UP) is now delivering its first cohort from phase 2 and is currently recruiting students for intake in October 2016. The extension of the CDT-UP greatly strengthens the research activity within the Centre for Innovative Manufacturing in Ultra Precision and has enabled the Centre to increase the scope of the research carried out within it. Phase 2 consists of 4 cohorts of 10 students, with applicant access ports from Cranfield University and the University of Cambridge.

The Centre for Doctoral Training will continue to develop its leading training and research environment that will deliver to industry highly skilled ultra precision engineers capable of making a significant impact on the ultra precision industrial landscape. The collaborating team from Cambridge and Cranfield Universities have increased the range of research topics and have widened the participating University supervisors through strengthened Centre collaborations across the Cambridge Departments of Material Science, Chemistry and Physics.

2016 saw the delivery of a new training programme in ultra precision metrology that has been developed with the support of world leading scientists and engineers at the **National Physical Laboratory** (NPL). This unique experience will greatly enhance the CDT students' research skills and competencies in advanced metrology, in addition to providing students with an appreciation of the important technologies being developed at NPL.

The Centre for Doctoral Training and the EPSRC Centre in Ultra Precision has a growing cohort of 35 ultra precision engineering PhD students across the two universities. It has recently extended its collaboration with Prof Richard Leach at the **University of Nottingham**, and has supported a number of PhD projects within his group, working on new optical metrology technologies. At the end of the CDT-UP programme in 2022, it will have delivered around 70 PhDs. This will make a significant impact on the ultra precision engineering landscape in the UK, which has established a firm and proven alliance of highly complementary academic and industrial organisations.



2015-2016 CDT cohort

CDT lab sessions at Cranfield University

The CDT-UP has seen a number of new PhD programmes established after the 2014/15 MRes cohort completed their first year in Sept 2015. There are now research collaborations with the **United States Air Force** (USAF) on processing carbon nano materials for energy applications, **Diamond Light Source**, on the development of precision optical tweezer technologies, and **Jaguar Land Rover** on the creation of new holographic displays for automotive applications.

In addition to providing excellent research and skills training, the Centre seeks the wider engagement of new industrial collaborations to provide its CDT students with interesting and challenging research problems that are faced by industry. Our new intake of CDT students has diverse backgrounds ranging from aerospace engineering, bioengineering, to chemistry. We look forward to the new challenges faced in 2016 and are primed to grow the strengths and capabilities of our ultra precision engineers.

Awards and Prizes

Tianqi Dong

Tianqi Dong (centre) at *ICALEO 2015*

Tianqi Dong, a PhD researcher at the **Institute for Manufacturing, University of Cambridge** won first prize for her paper "Evaluating femtosecond laser ablation of graphene on SiO_2/Si substrate" at the *International Congress on Applications of Lasers & Electro–Optics (ICALEO®)* held in Atlanta, USA, 18-22 October 2015.

The *International Congress on Applications of Lasers & Electro-Optics (ICALEO®)* has a 33 year history as the conference where researchers and end-users meet to review the state-of-the-art in laser materials processing, laser micro-processing, and nano-manufacturing as well as predict where the future will lead. From its inception, *ICALEO®* has been devoted to the field of laser materials processing at macro, micro, and nanoscales and is viewed as the premier source of technical information in the field.

Andrew Payne

Andy's winning photo of a Titanium "comet"

The annual **University of Cambridge** engineering photo competition showcases the breadth of engineering research at the University, from objects at the nanoscale all the way to major infrastructure.

The competition, sponsored by **ZEISS**, international leaders in the fields of optics and optoelectronics, had five categories this year. Alongside those for first, second and third place, the ZEISS SEM prize was awarded for a micrograph captured using an electron microscope, and a Head of Department's prize for the photo or video with the most innovative engineering story behind it.

PhD researcher Andy Payne based at the **Institute for Manufacturing, University of Cambridge** won second prize for his image of a titanium "comet".

Quality and Metrics

	Target	Achieved at Year 4 point
Publications		
Journal papers 1 paper per 1 research staff person year	55	59
Keynotes given by Centre investigators and researchers 1 keynote given at international conference per 2 staff person years	25	22
Student keynotes /awards 1 student provided keynote or presentation award per 3 staff person years	8	5
Outreach		
Strategic outreach meetings 3 per year to establish UP Centre as UK hub	15	22
Development		
PhDs completed Directly funded by the Centre	16	1
PhDs completed Funded by the CDT in Ultra Precision	30	N/A
Promotion of 40% of staff engaged in UP Centre	8	6
40% of PhDs to hold RA, engineer or science positions in UK	12	N/A
Partnerships		
Maintain original partners 75% still active after 5 years	3	3
Engage new industrial partners 2 per year	10	9
Uptake		
Centre main project taken forward by industry	3	2
Centre		
Planning and delivery Hold overall programme by delivering Gantt deliverables and milestones	22	13
Added value to UP Centre Secure additional funding equal to EPSRC original funding	£6.8m	£7.5m

Centre Publications

Journal Publications

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Appendices

Steering Group

Dr Paul Atherton (Chairman) Nanoventures

Gerard Davies EPSRC

Prof Daping Chu University of Cambridge

Prof Chris Evans University of North Carolina at Charlotte

Chris Rider University of Cambridge

Andrew Hurst Qioptiq

Dr Richard Langford University of Cambridge

Prof Richard Leach University of Nottingham

Dr Peter MacKay Gooch & Housego

Prof Bill Milne University of Cambridge

Paul Morantz Cranfield University

Martin O'Hara Cranfield University

Prof Bill O'Neill (Director, Centre for Doctoral Training in Ultra Precision) University of Cambridge

Neil Prescott Heidenhain (GB) Ltd

Dr Phil Rumsby M-Solv Ltd

Prof Paul Shore National Physical Laboratory

Dr Tom Taylor Centre for Process Innovation Ltd

Prof Tim Wilkinson University of Cambridge

Andy Sellars Innovate UK

Industrial Supporters

3D Evolution

Aerotech

Aixtron

ALE Ltd

Amplitude Systèmes France

Base4Innovation Ltd

Cambridge X-Ray Systems

Carl Zeiss Germany

Centre for Process Innovation

Cheyney Design & Development

Contour Fine Tooling Ltd

Fanuc CNC UK Ltd

Fives Cinetic

Gooch & Housego plc

Hamamatsu Photonics (UK) Ltd

Heidenhain (GB) Ltd

Hexagon Metrology Ltd

Hitachi High-Technologies Europe Ltd

iXscient Ltd

Keating Specialist Cylinders Ltd

Laser 2000 UK Ltd

Loxham Precision

Microsharp Corporation Ltd

Nokia Finland

NSK Ltd Japan

Oxford Instruments

Plarion Ltd

Plasma Quest Ltd

Qioptiq

Renishaw plc

Sphere Medical Ltd

SPI Lasers

The Worshipful Company of Engineers

UPS^2

Veeco Instruments Ltd

Westwind

Xradia Inc USA

Science Collaborators

Agency for Science, Technology and Research Singapore

Air Force Office of Scientific Research (USAF) USA

Cambridge Analytical Biotechnology Laboratory

Centre of Science Technology and Innovation Policy

CERN Switzerland

Commercial Aircraft Corporation of China Ltd China

Cork Institute of Technology Ireland

Diamond Light Source

Eindhoven University of Technology The Netherlands

Hydrolight Ireland

Innovate UK

Nanjing University of Aeronautics and Astronautics China

National University Defence Technology China

Riken Japan

University of Hanover Germany

University of Leeds

University of Michigan USA

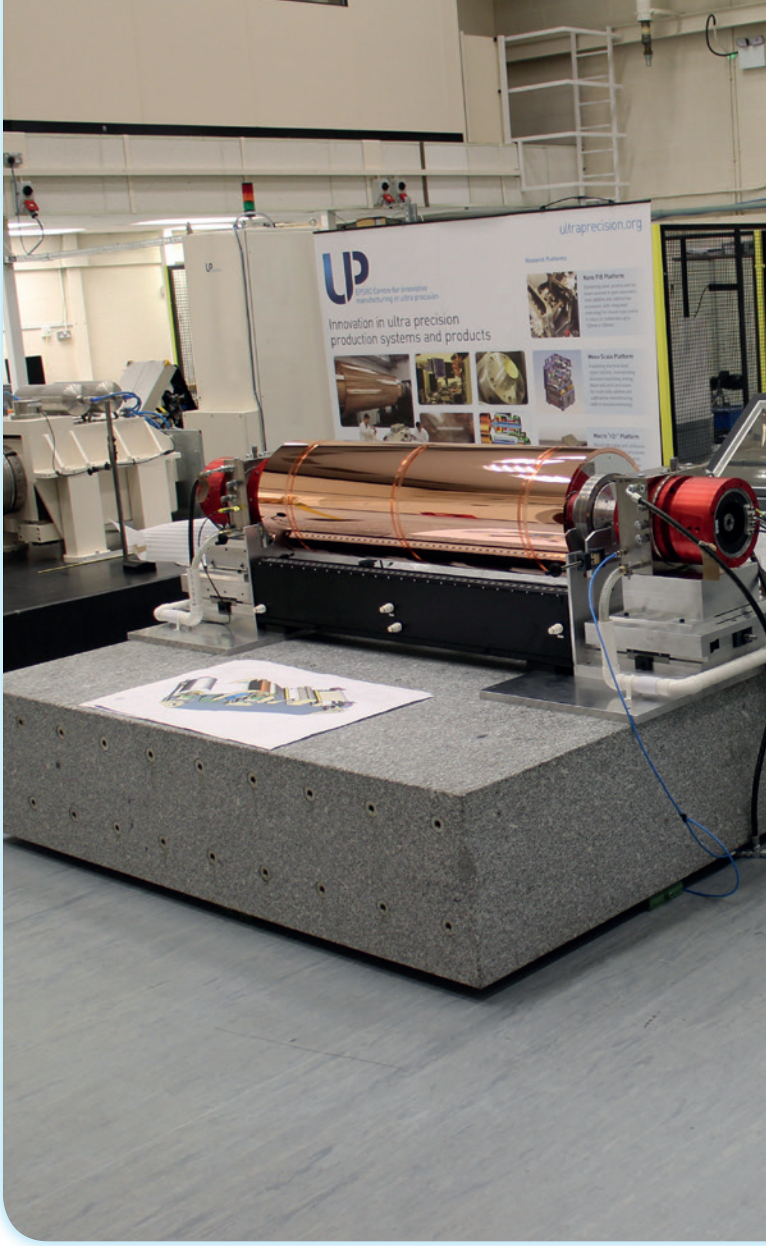
University of Montpellier France

University of North Carolina at Charlotte USA

University of Nottingham

University of Tokyo Japan

Wroclaw University of Technology Poland



Centre Management Team

Dr Paul Comley Cranfield University

Prof Daping Chu University of Cambridge

Dr Richard Langford University of Cambridge

Dr Andrew Lewis National Physical Laboratory

Prof Bill Milne University of Cambridge

Paul Morantz – (Centre Director) Cranfield University

Martin O'Hara Cranfield University

Prof Bill O'Neill (Director, Centre for Doctoral Training in Ultra Precision) University of Cambridge

Dr Nick Walker iXscient Ltd

Prof Tim Wilkinson University of Cambridge

Administration Team

Ms Anne Fiorucci Cranfield University

Mrs Sophie Fuller University of Cambridge

Mrs Enza Giaracuni Cranfield University

Centre Partners

Cranfield University

University of Cambridge

National Physical Laboratory

Research Projects

Researcher Name	University	Project Title	Year Project Started
Jonathan Abir	Cranfield University	Design and Control of a Compact Ultra Precision Machine Tool for High Dynamic Performance	2013
Dulce Augilar-Garza	University of Cambridge	Design, Fabrication and Characterisation of Hierarchical Branching Vascular Networks	2014 (MRes) 2015 (PhD)
Matt Bannister	University of Cambridge	The Interaction Between Ultrafast Lasers and FIB Machined Silicon for the Removal of Implanted Gallium	2012 Now writing up PhD thesis
James Barrington	Cranfield University	A Precision Fibre Optic CO_2 Sensor CO_2 Sensor	2015
Adam Bennett	Cranfield University	Microwave Generated Plasma Figuring for Ultra Precision Engineering of Optics for Aerospace and Defence	2014
Patrick Bointon	The University of Nottingham	The Development of Non-Contact Methods for Measuring the Outside Geometry of AM Parts	2015
Sam Brown	University of Cambridge	Design and Development of Solid State Additive Manufacturing Techniques	2014
Xin Chang	University of Cambridge	Spatial Light Modulators and its Application in Computer Generated Holograms	2014 (MRes) 2015 (PhD)
Clare Collins	University of Cambridge	Ordered Nanomaterials for Electron Field Emission	2013 (MRes) 2014 (PhD)
Lily Delimata	University of Cambridge	MRes in Ultra Precision Engineering	2015 (MRes)
Alex Diaz	University of Cambridge	Development and Optimisation of an Optofluidic Nano Tweezers System for Trapping Nanometre Crystals for Synchrotron X-Ray Diffraction Experiments	2014 (MRes) 2015 (PhD)
Tianqi Dong	University of Cambridge	Evaluating Femtosecond Laser Ablation of Graphene on $Si0_2$/Si Substrate	2014
Wenhe Feng	University of Cambridge	Precision Glass Microstructuring Using Femtosecond Laser Induced Chemical Etching	2012 Submitted 2015
Will Fowler	University of Cambridge	MRes in Ultra Precision Engineering	2015 (MRes)
Nadeem Gabbani	University of Cambridge	MRes in Ultra Precision Engineering	2015 (MRes)
Daniel Gortat	University of Cambridge	Anode Materials for High Power Microwave Devices	2014 (MRes) 2015 (PhD)
Andrew Graham	Cranfield University	Ultra Precision Control of a Reel-to-Reel Process	2015
Jiho Han	University of Cambridge	High Power Laser System with Built-in Dynamic Beam Shaping Capabilities	2012 (MRes) 2013 (PhD)
Katjana Lange	University of Cambridge	MRes in Ultra Precision Engineering	2015 (MRes)
George Meakin	University of Cambridge	Display Motion Error Reduction through Novel Binary Dithering Schemes	2013 (MRes) 2014 (PhD)

Researcher Name	University	Project Title	Year Project Started
Laurent Michaux	University of Cambridge	Control of Residual Stress and Failure Mechanisms for CS and LCS	2012
James Norman	Cranfield University	Precision Metrology for Large Freeform Non-Specular Surfaces	2014
Francisco Orozco	University of Cambridge	Laser Processing Of Carbon Nanotube Fibres and Films	2012 (MRes) 2013 (PhD)
Jon Parkins	University of Cambridge	Novel Energy Delivery Techniques for Laser Additive Manufacturing from Metal Powders	2012 (MRes) 2013 (PhD)
Andy Payne	University of Cambridge	Multiple-Beam Powder Bed Fusion Additive Manufacturing	2012
Matt Pryn	University of Cambridge	Jaguar Land Rover iHUD Project	2013 (MRes) 2014 (PhD)
James Ryley	University of Cambridge	MRes in Ultra Precision Engineering	2015 (MRes)
Jaliya Senanayake	University of Cambridge	Optimising the Performance of Fibre Optic Sensors using Holography	2012
Yoanna Shams	University of Cambridge	An Inkjet/Ultrafast Laser Hybrid for Digital Fabrication of Biomedical Sensors	2013 (MRes) 2014 (PhD)
Danny Sims-Waterhouse	The University of Nottingham	Development of Camera-Based Systems for Micro-Coordinate Metrology	2015
Jyi Sheuan Ten	University of Cambridge	High Speed Mask-Less Laser Controlled Precision Micro Additive Manufacture	2013 (MRes) 2014 (PhD)
Chris Williamson	University of Cambridge	Smectic A Liquid Crystal Display Panel Defect Generation	2011 Completed 2015
Chris Wright	University of Cambridge	Ultra Precision Hybrid Laser-FIB Platform	2013 (MRes) 2014 (PhD)
Peter Xia	Cranfield University	Diamond Machinable Coatings for Fluid Film Systems	2013
Karen Yu	University of Cambridge	Control System for Ultra Precision Processing	2012
Nan Yu	Cranfield University	Advancement of Plasma Figuring Technology to Reduce MSF Errors of Metre-Scale Optical Surfaces	2013

Contact us

EPSRC Centre for Innovative Manufacturing in Ultra Precision

Precision Engineering Institute, Building 90,
Cranfield University, Cranfield, Bedfordshire,
MK43 0AL, UK.

Contact: Mrs Enza Giaracuni
Email: info@ultraprecision.org

EPSRC Centre for Doctoral Training in Ultra Precision

Centre for Industrial Photonics,
Institute for Manufacturing, University of Cambridge,
17 Charles Babbage Road, Cambridge,
CB3 0RS, UK.

Contact: Mrs Sophie Fuller
Email: sg523@cam.ac.uk

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www.ultraprecision.org

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