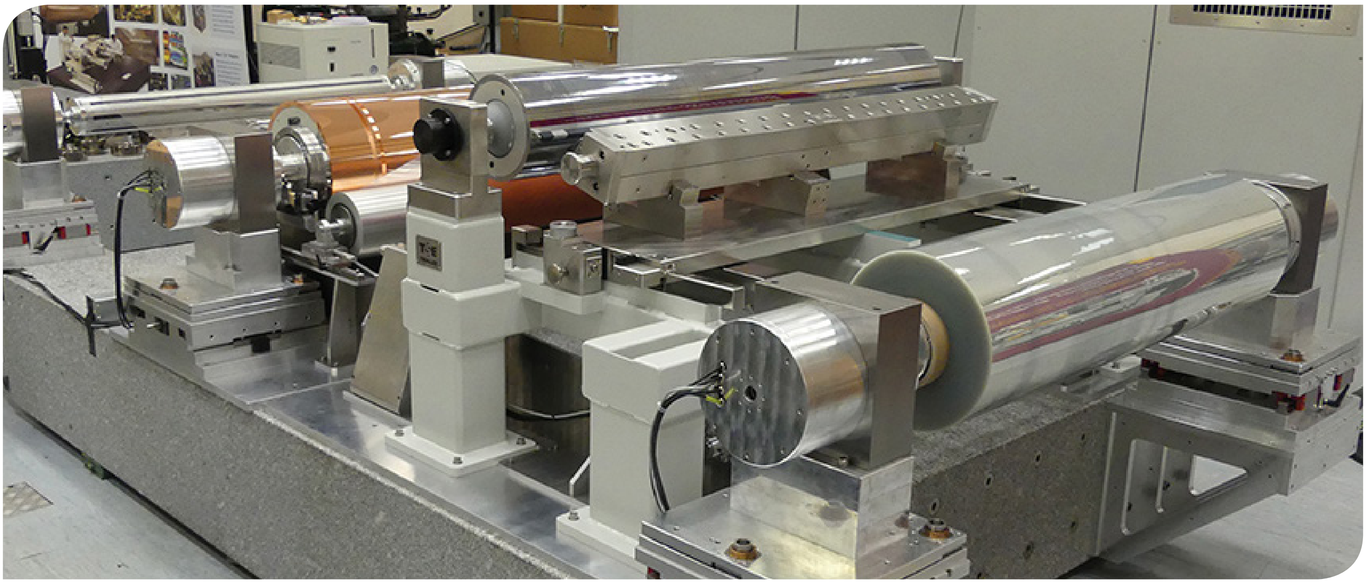
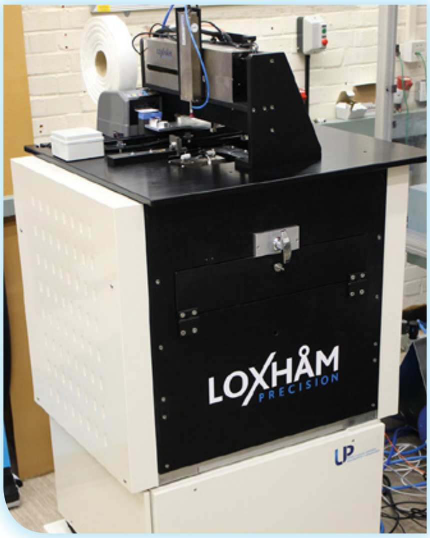
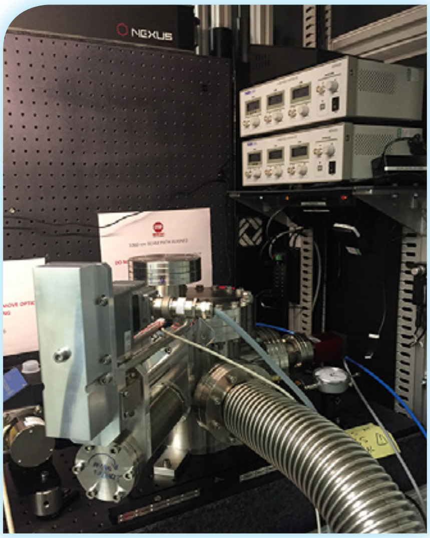
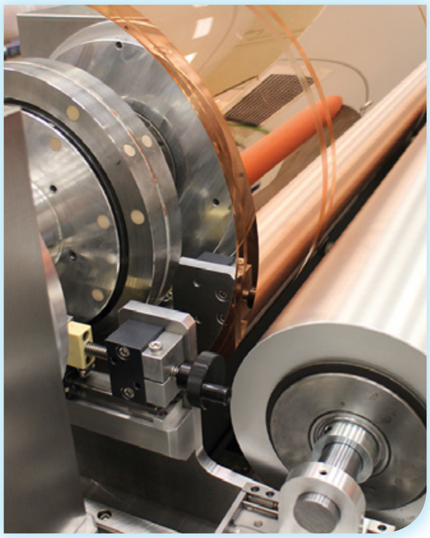
EPSRC Centre for innovative manufacturing in ultra precision

EPSRC
Pioneering research and skills









Final Report

2016

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**, **National Physical Laboratory**, **University of Nottingham**, **euspen Ltd**, **Vandyke School** and **Bedford School**.

Executive Summary

This final report provides an overview of the achievements of the 5 year duration of the EPSRC Centre for Innovative Manufacturing in Ultra Precision. Overviews of each aspect of the Centre are provided covering: national strategy and educational outreach, core research, research platforms and achieved business translation.

Our goal has been to better position UK companies in securing wealth creation from ultra precision manufacturing of emergent products and those demanding high accuracy for their own product performance, but also achieving high accuracy during arduous rapid production conditions. Much of our research has been targeted towards realisation of major research platforms. This research has been closely coupled to UK companies within the manufacturing supply chain who have significantly contributed with regards to expertise and the sub-systems for the Centre's research platforms and demonstrators which today represent truly world leading highly bespoke ultra precision research systems.

Recognising UK manufacturing supply chains for production systems and machine tools have been "hollowed out". The Centre endeavoured to create (seed) new UK manufacturing supply chains for next generation production systems. Our research efforts have helped create new products and new spin out companies from the Centre's research; these are testament to our success.

Whilst much of the research was of a low TRL nature, the Centre spanned the TRL levels with higher TRL level activity in the design and build of the three significant research platforms. At the end of the Centre's 5 year term our research platforms now demonstrate medium to high TRL characteristics. Of the three research platforms, one is being sold as a product of a Cranfield spin out; **Loxham Precision Limited**. The second forms a unique laser processing facility at Cambridge, whilst the third is a unique roll to roll research facility that provides Cranfield a basis for industrial scale roll to roll film processing research. This roll to roll platform, in combination with a roll fabrication capability established by a second spin out from Cranfield, **UPS^2 Limited**, has established an internationally recognised roll to roll manufacturing research and development capacity for the UK, with a strong UK based manufacturing supply chain.

The aligned Centre for Doctoral Training in Ultra Precision Engineering (CDT-UP), led by Professor Bill O'Neill at the **University of Cambridge**, has become a world leading and highly vibrant research community in the ultra precision field. Professor O'Neill's passion, style and enthusiasm has shown through and made this Centre for Doctoral Training internationally recognised for academic rigour, technical excellence and innovation. Student sponsors provide evidence of the broad industrial demand for ultra precision technologies. The CDT-UP 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 unique ultra precision educational partnership that is able to deliver highly skilled ultra precision engineers and scientists.

Our National Strategy Programme led by Martin O'Hara and Enza Giaracuni has been delivered throughout the UK. Activities included road mappings, industrial workshops, industrial short courses, international secondment, prestige lectures and many school interactions. We have also been delighted with the success of our educational outreach programme Watch It Made®. With the financial support of the **Royal Academy of Engineering**, **Vauxhall Motors**, the **National Physical Laboratory** and numerous other UK engineering companies, the Centre provided an opportunity to practice precision engineering by manufacturing a personally designed watch to over 600 school children aged between 10-13 years old. We are very hopeful that this "learn by proudly engineering your own quality product" is a new mechanism for enthusing the next generation of engineers.

And rightly so, we will be assessed against our original KPIs including those of quality publications, invited keynotes, partnerships and collaborations and perhaps most important of all, the career development of our staff. We record these achievements in a clear and simple tabulated manner.

I'd like to thank all those who contributed to the EPSRC Centre for Innovative Manufacturing in Ultra Precision and thank the EPSRC Manufacturing the Future staff for their support throughout the duration of the Centre. I'd be pleased to receive thoughts and comments on any aspects of the work described in this final report.

Professor Paul Shore FREng
Principal Investigator

National Strategy Programme

The National Strategy Programme commenced in 2013, when a separate EPSRC funding programme was initiated to enable the research and technologies being developed by the Centre to be disseminated better to industry. This also enabled closer interaction with industrialists to help direct the ongoing and future research activities. Some of the activities that have been covered under the National Strategy Programme started prior to the formal programme launch.

The Centre's National Strategy Programme is based around 4 elements:

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

These 4 elements each have a series of activities, services and outreach programmes around them or integrated into the other research as support activities.

Web Services

Our web service provision breaks down into 2 areas; the website and social media.

Website

We have used the website **www.ultraprecision.org** for transmitting all of the research activities, annual reports, the latest news on students and other activities, and used as a portal for the Centre's outreach event registrations, hence the website became the Centre's primary "go to" location for information. The website has seen a great uptake of visitors and daily hits, achieving over 1 million hits per annum for the past 2 years and expected to again achieve over 1 million hits in 2016 (Figure 1).

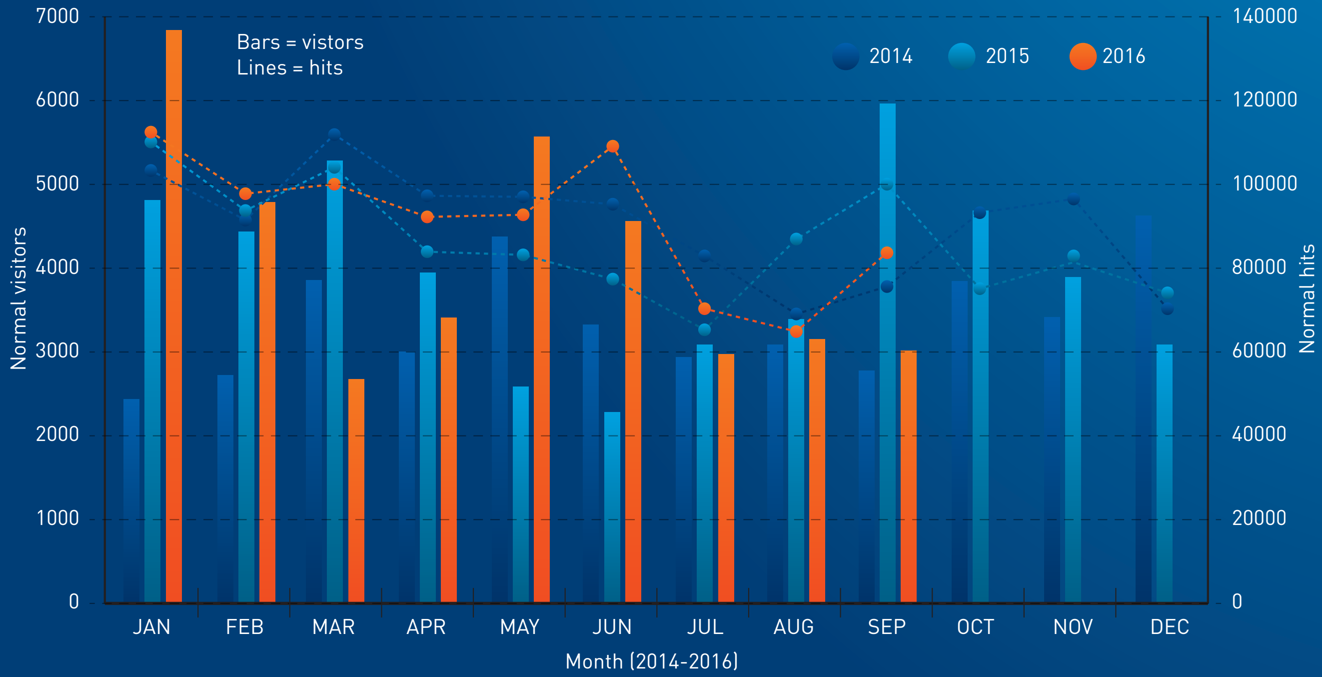


Figure 1: Website statistics: hits and visitors 2014-2016

Note: excludes robot searches, static data

The distinct number of visitors (different visits per day), has risen steadily over the 3 years the site has been active, while the number of hits remains relatively stable over the past 2 years. This increase in visitors, while hits remain stable, suggests visitors are finding the site easier to navigate after their first connection, i.e. they come back straight to where they know they can find the information.

The Centre added to the utility of the site by including a UK facilities database of ultra precision technologies in UK academic and industrial laboratories. This lists equipment that is available for use at commercial rates and is a free-to-list database (Figure 2). The website also has a UK ultra precision community page, where businesses in the ultra precision technology sector can list for free. This has been a useful tool to some of the industrial supporters, but hasn't gained the traction we would have liked compared to our off-line database (covered later), despite being a free-to-list service (Figure 3).

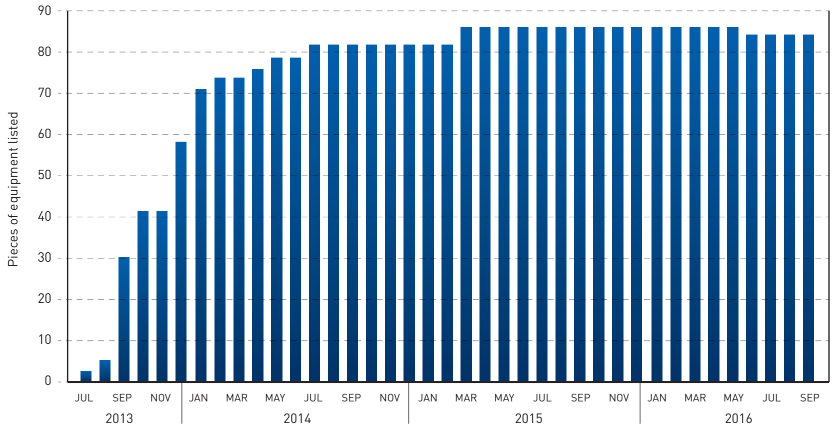


Figure 2: UK facilities listed on the database

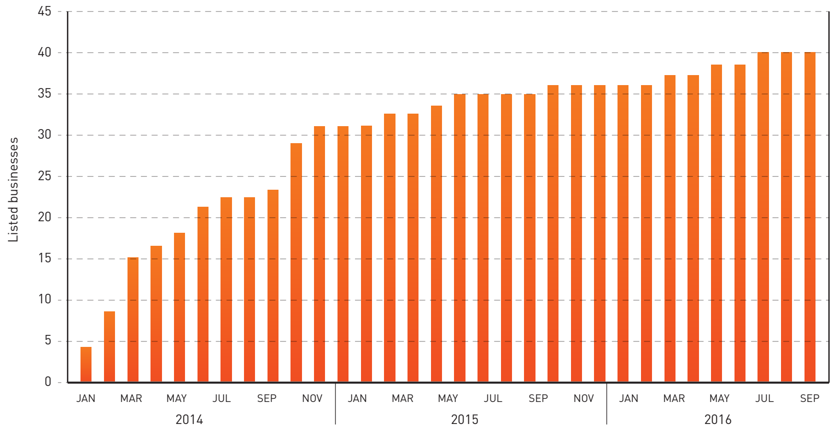


Figure 3: Ultra precision community listings

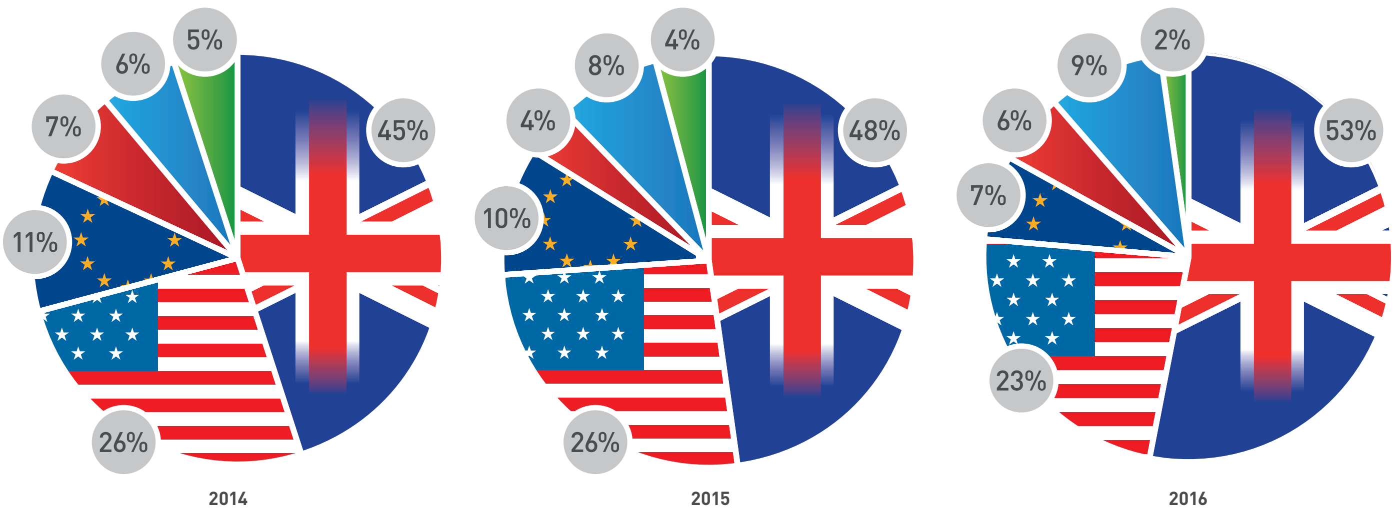


Figure 4: Geographic origin of wesbite hits per year 2014-2016

Key: Eastern Europe South East Asia Rest of World

The website is an easy to access portal for overseas parties interested in ultra precision technologies in the UK. While we have made some direct overseas contacts, the site is undoubtedly the most cost effective means of communication outside of the UK. The engagement of overseas visitors has grown over the period of the Centre from just over 40% of site visitors in 2013 to just over 50% today. The site is in English language only, but shows a good spread in countries where English is not the first language (Figure 4).

Overall the site has proven a very useful tool to both the Centre and the ultra precision community, both in the UK and overseas.

Note: we discount all robot searches and static data from our web site statistics.

Social Media

The Centre's social media is broken down into 3 distinct platforms with specific target audiences in mind; Facebook for student engagement, LinkedIn for industrial and academic engagement and Twitter for business news, events and general interest items.

Of the 3 social media platforms Twitter **(@UPrecisionUK)** has proved the most useful with over 650 followers at the time of writing this report and gained significant retweets and likes and over 4,700 tweets broadcast (Figure 5). LinkedIn has been relatively successful, but on a much smaller scale. The target industrial audience was successfully engaged and the LinkedIn group **Ultra Precision UK Network** has an active membership that has had a steady growth over the past 3 years. The student engagement via Facebook has been the least successful.

It is possibly not the best media for engaging in a research programme and it is possible many of the students do not use Facebook today preferring other social media channels. The Centre also has a YubeTube channel **CranCamUP**, where student project videos can be viewed.

While it can be difficult to determine the geographic spread of most social media engagement, it is fair to say that the majority of those engaged in these channels are from the UK. We have access to a map of the Twitter followers which shows 82% are UK based (Figure 6), with the majority of other followers being in North America and then EU countries. This is a much narrower geographic engagement than the website or the networking engagement provides, but is proving a useful resource for the UK ultra precision community.

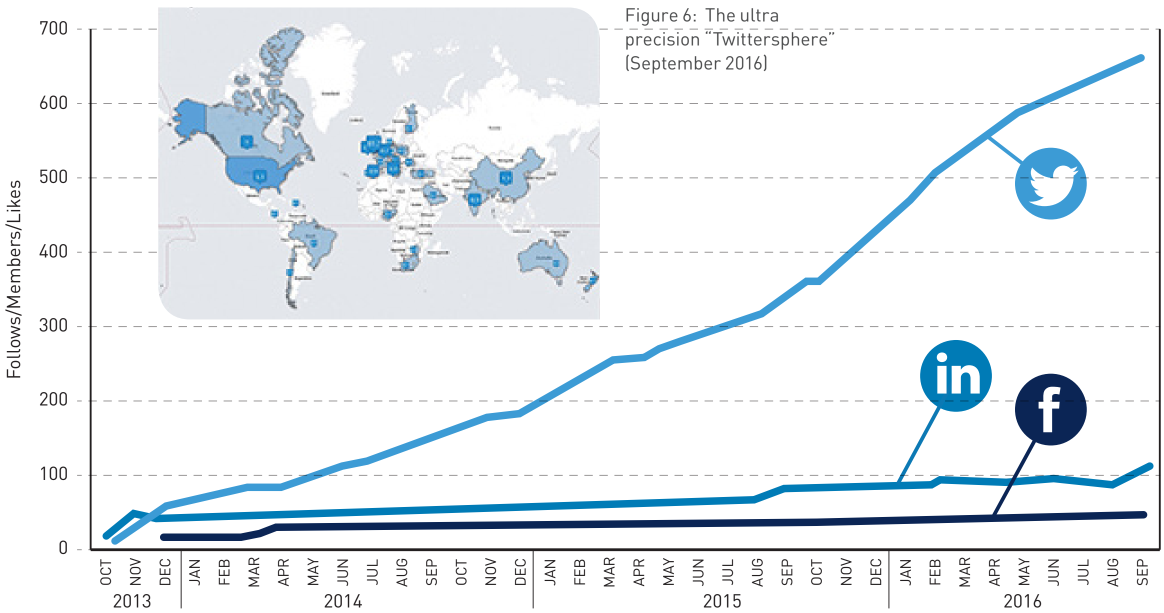


Figure 6: The ultra precision "Twittersphere" (September 2016)

Figure 5: Social media stream uptake

Ultra Precision Network

The feedback from our national outreach networking events has continued to be very high over the course of the programme; we have consistently delivered above expectations in all areas of the event activities we have delivered (Figure 7). The events have been able to target very specific areas of industrial activity or academic research, allowing a tight focus on specific technologies or processes and hence making them an effective engagement tool for specific businesses (there is less irrelevant information). Another benefit we have been able to derive for our delegates is to visit UK facilities that they may not have been aware of, hence we have visited the **National Physical Laboratory**, the **UK Astronomy Technology Centre**, **UPS²**, High Value Manufacturing Catapults (**Manufacturing Technology Centre** and **Centre for Process Innovation**) as well as some businesses that have been able to host us and offer a facilities tour such as **Renishaw**. This has enabled the networking events to provide attendees an insight beyond the specific technology that is the subject matter and see for themselves what other centres in the UK can offer and how they might engage.

The events have brought the Centre into contact with many new businesses, over 90 that had never been in contact with the Centre or either Cranfield or Cambridge Universities prior to these events (Figure 8). Many of these are small-to-medium enterprises (SME's). Some of the relevant businesses are clustered in specific geographic regions of the UK, hence our geographic spread of activities has enabled many SME's to attend events that have been local to themselves and typically more relevant as they may be in the supply chain to the facility at which the event is held. The Centre believes the *"taking our events to the community, rather than expecting the community to come to us"* approach is one of the reasons it has been so successful in engaging SME's and so many new businesses. These events and the approach to them also helped with one of the Centre's other ambitions; to reconnect the UK ultra precision supply chain.

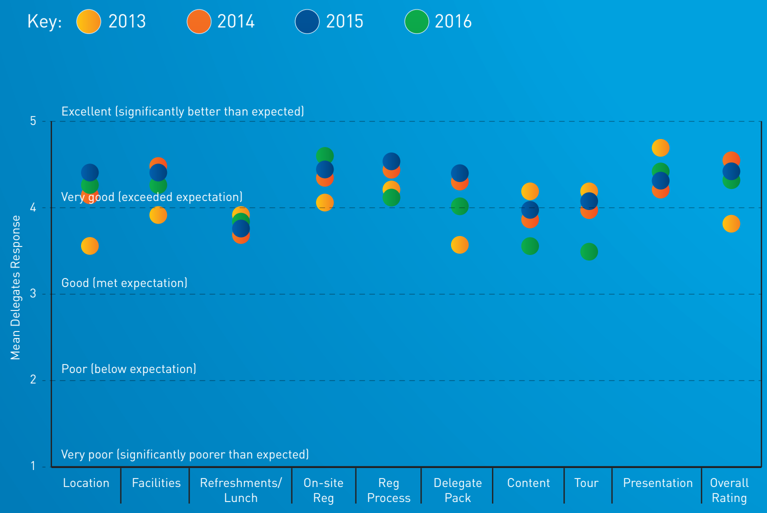


Figure 7: Networking events delegate feedback

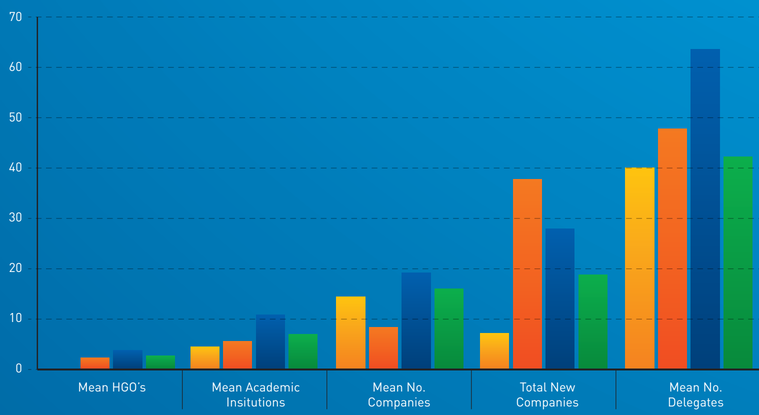


Figure 8: Background of delegates at networking events

National and International Engagement

Although the Centre's networking events were all UK based, partly due to its funding structure, it has been able to engage with companies, research organisations and Universities outside of the UK over the period of its activities, and not just through the website (Figure 9). The Centre had several overseas presenters and delegates at its networking events. It has also had speakers from **CERN** and **ASML** to present at its prestige lectures, hence have made efforts to increase the outreach beyond the UK's shores.

The international outreach activity was supported by exhibiting at a selective number of overseas conferences, in particular *Photonics West 2014* in San Francisco, *eu**spen** 2014* in Dubrovnik, *eu**spen** 2015* in Leuven and *Precision Fair 2014* in Veldhoven. In two of these exhibitions (*eu**spen** 2015* and *Precision Fair 2014*) the Centre provided a SME exhibition cluster stand to 3 UK businesses, allowing them to also exhibit at these events for a fraction of the full exhibition cost. This enabled further promotion of the UK research and industrial base in ultra precision technologies to overseas engineers and industrial buyers.

Figure 9: International outreach (non UK) connections

In the UK itself the Centre has achieved an excellent spread of engagement with UK businesses, both through its networking events, trade exhibitions, industrial visits and other outreach activities. Figure 10 shows businesses that have directly engaged with the Centre and are part of the ultra precision community of businesses.

A Customer Relationship Management (CRM) database of contacts has been set up for further work and analysis when new research programmes and sector specific manufacturing opportunities arise in the future. In total the Centre has made direct connections to 398 UK and 216 non-UK organisations, roughly split 60% industrial and 30% academia, with non-government organisations and media making up the final sectors (Figure 11).

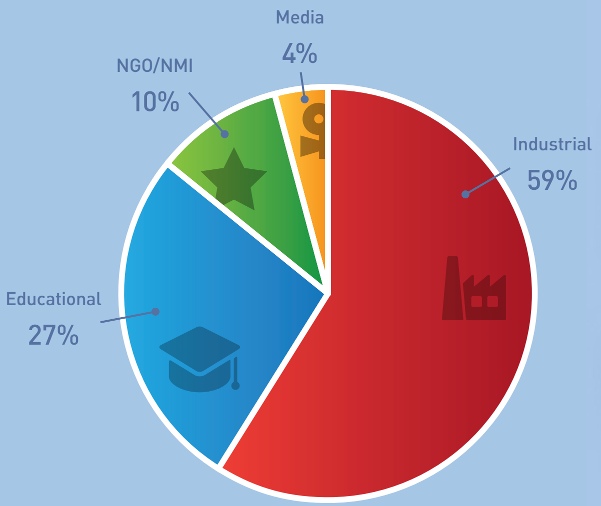


Figure 11: Sector split of connections made by the Centre

Figure 10: UK businesses that have made a connection to the Centre

Educational Programme

The educational outreach programme was one of the greatest successes of the Centre's activities, in particular Watch it Made®. Although this did dominate the reported educational outreach activities, this was not the only activity.

Throughout the duration of the Centre, staff members from both Universities were invited to various local schools to provide talks on precision engineering subjects and careers in engineering to a range of young learner ages (from pre-GCSE to A-level). These were on a relatively ad-hoc basis, although once a visit had been made it was usual for it to become an annual event, for example the *Samuel Whitbread Academy Careers Fair*. The Centre has also hosted tours for local schools and the *London International Youth Science Forum* which visits **Cranfield University** on an annual basis. Over the past years, the **Institute for Manufacturing** at the **University of Cambridge** welcomed thousands of visitors, including students to the annual *Cambridge Science Festival*.

The Centre has also hosted work experience and internship placements at both campuses to students at GCSE level and above.

The Centre delivers the *Precision Engineering Industrial Short Course* each September at **Cranfield University**, specifically targeting industrialists. The course attracted delegates from around the globe and is expected to continue. This was also the first eu**spen** accredited educational programme, outside of The Netherlands, for their European Certified Precision Engineer (ECP2) continuing professional development programme, where delegates may accrue credits toward this prestigious post graduate qualification.

The *Energy Processing Technologies* short course at the **University of Cambridge** led by the **Institute for Manufacturing** was also offered to industrial delegates for the first time in 2015. This too will be aiming to become ECP2 accredited once the next phase of the ECP2 programme is complete, and again is expected to continue post Centre funding.

The Centre's primary educational outreach programme Watch it Made®, covered in greater detail later in this report, was developed as an activity in which young learners were able to design, manufacture and assemble their own personalised wrist watch. The programme was developed initially as a studio based activity at **Cranfield University**, with students visiting the studio and completing the activity in groups over half a day. The watch making experiences were delivered at science festivals and at the **Glasgow Science Centre** as part of the *3rd Annual EPSRC Manufacturing the Future Conference* in 2015 and at the **National Physical Laboratory** to celebrate the 60th anniversary of the atomic clock. Watch it Made® is to be established at the **National Physical Laboratory** in the near future so the watch making experiences may continue in a larger catchment area and hence enable the programme to reach out to more students.

Translation to Wealth

Throughout the past few years, the Centre has tried some commercial activities such as operating an overseas exhibition SME cluster stand and examined the cost base of running a UK membership model to support future outreach. The only approach that could secure adequate levels of financial support to continue the programme of activities it has so far achieved would be through a funded programme. To this end the Centre submitted a Manufacturing Research Hub bid to the **EPSRC** in 2016, but was unsuccessful in the final round. While the research itself will continue at both campuses via alternative funding mechanisms, the outreach activity concludes with the end of the Centre.

Outreach

Throughout the duration of the programme, the Centre organised numerous networking events as part of its National Strategy Programme, aimed at industrial and academic audiences. In addition, the Centre staff also attended external events as an exhibitor or speaker. In terms of its own organised events, the Centre's philosophy *"we go out to our community, rather than expecting the community to come to us"* has proved invaluable to delegates.

Some of the events were held in collaboration with the **European Society for Precision Engineering and Nanotechnology** (eu**spen** Limited) and the **EPSRC Centre in Laser Based Production Processes**. Relationships were forged with other EPSRC Centres for Innovative Manufacturing including the **EPSRC Centre in Photonics**, **EPSRC Centre in Advanced Metrology** and the **EPSRC Centre in Large Area Electronics**.

The Centre would like to thank eu**spen**, the **EPSRC Centre in Laser Based Production Processes**, and **Andor Technology** for co-sponsoring selected outreach events. Additionally the Centre would like to thank venues for providing the use of their conference facilities in kind.

Events organised and delivered by the Centre 2011-2015:

2011

Roadmap for the EPSRC Centre for Innovative Manufacturing in Ultra Precision, Kavli Royal Society International Centre, Chicheley Hall, Chicheley, Buckinghamshire, 17 October 2011.

2012

Precision Engineering at CERN: Future Challenges and Opportunities, CERN, Switzerland 2-3 May 2012. A workshop held in collaboration with eu**spen** Ltd.

Broad Energy Beam Processing Technologies Workshop, Kavli Royal Society International Centre, Chicheley Hall, Chicheley, Buckinghamshire, 29 August 2012.

2013

Integrated Knowledge Centre in Ultra Precision Structured Surfaces: Review Meeting, Royal Academy of Engineering, London, 20 June 2013.

Prestige Lecture by Professor Alexander Slocum of MIT, USA: Renewable Energy Machines, Cranfield University, 8 July 2013.

Metrology Technologies to Enable Reel to Reel Processing of Emerging Technologies, National Physical Laboratory, Teddington, Middlesex, 20 November 2013.

2014

Plastic Electronics Fabrication Technologies, Centre for Process and Innovation Ltd, Sedgefield, 19 February 2014.

Future Display Technologies and Production Demand, Institute for Manufacturing, University of Cambridge, 1 April 2014.

Prestige Lecture by Dr Stephen Myers of CERN: The Engineering Needs for Particle Physics and the CERN Large hadron Collider (LHC), Cranfield University, 8 April 2014.

Ultra Precision Research Student Conference, Cranfield University, Bedfordshire, 6 May 2014.

Reel to Reel Road Mapping Workshop, Cranfield University, Bedfordshire, 15 May 2014.

Reel to Reel Production Technology, Sustainable Product Engineering Centre for Innovative Functional Industrial Coatings Innovation Knowledge Centre (SPECIFIC IKC), Swansea, 25 June 2014.

Micro Surface Structuring, OpTIC Centre, St Asaph, 19 November 2014.

2015

Micro Manufacturing, The Manufacturing Technology Centre, Coventry, 25 February 2015. A workshop held in collaboration with eu**spen Ltd**.

Optical Demands of Astronomy, UK Astronomy Technology Centre, Edinburgh, 16 June 2015.

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

Solar Thermal and Concentrating Solar Power: Technology and Applications, Cranfield University, Bedfordshire, 1 December 2015.

Prestige Lecture by Prof Gillian Wright MBE, FRSE: James Webb Space Telescope, Cranfield University, Bedfordshire, 31 March 2015.

Ultra Precision Manufacturing Conference, **University of Cambridge**, 12 May 2015.

Events the Centre exhibited at 2011-2015

2012

12th International Conference and Exhibition of the European Society for Precision Engineering and Nanotechnology, Stockholm, Sweden, 4-8 June 2012.

2013

Innovate UK 2013, Business Design Centre, London, 11-13 March 2013.

National Manufacturing Debate, Cranfield University, Bedfordshire, 21 May 2013.

3th International Conference and Exhibition of the European Society for Precision Engineering and Nanotechnology, Berlin, Germany, 27-31 May 2013.

2nd Annual EPSRC Manufacturing the Future Conference, Cranfield University, Bedfordshire, 17-18 September 2013.

11th International Conference on Manufacturing Research (ICMR), Cranfield University, Bedfordshire, 19-20 September 2013.

2014

EPSRC Centre for Innovative Manufacturing in Medical Devices Launch, Metropole Hotel, Leeds, 10 January 2014.

SPIE Photonics West 2014, The Moscone Center, San Francisco, USA, 4-6 February 2014.

MACH 2014, NEC Birmingham, 7-11 April 2014.

National Manufacturing Debate 2014, Cranfield University, Bedfordshire, 21 May 2014.

14th International Conference and Exhibition of the European Society for Precision Engineering and Nanotechnology, Dubrovnik, Croatia, 1-6 June 2014.

3rd Annual EPSRC Manufacturing the Future Conference, Glasgow Science Centre, Glasgow, 23-24 September 2014.

Precisiebeurs 2014, Veldhoven, The Netherlands, 12-13 November 2014.

2015

National Manufacturing Debate 2015, Cranfield University, Bedfordshire, 20 May 2015.

15th International Conference and Exhibition of the European Society for Precision Engineering and Nanotechnology, Leuven, Belgium, 1-5 June 2015.

4th Annual EPSRC Manufacturing the Future Conference, University of Cambridge, 17-18 September 2015.

Samuel Whitbread Academy Careers Fair, Shefford, Bedfordshire, 20 October 2015.

INTERNATIONAL YEAR OF LIGHT 2015

2015 was the International Year of Light and the Centre registered 3 of its organised events in the UK programme for these celebrations: *Prestige Lecture by Prof Gillian Wright* at **Cranfield University**, *Optical Demands of Astronomy* at the **UK Astronomy Technology Centre**, Edinburgh, and *Laser Processes in Ultra Precision Manufacturing* held during *Photonex 2015*, Coventry.

Our own events

External events – the Centre attended in 2016

March 2016

euspen's Special Interest Group Meeting: Thermal Issues

Prague, Czech Republic.

Nan Yu, PhD researcher at **Cranfield University**'s Precision Engineering Institute attended the *eu**spen** Special Interest Group Meeting: Thermal Issues* in Prague, Czech Republic, 17-18 March 2016. This is an annual event which brings together leading expertise globally to an open forum for focused presentations and discussions on thermal issues in manufacturing. Nan presented his research 'Energy balance investigation of an inductively coupled plasma torch for plasma figuring' and participated in the technical tours held at local machine tool manufacturer **KOVOSVIT MAS** and labs at the **Czech Technical University**.

April 2016

Event speakers with Centre staff Martin O'Hara (left) and Enza Giaracuni (right)

Event lab tours

Optical Materials Day

Cranfield University, UK.

The Centre was pleased to collaborate with **Optence e.V** base in Germany to deliver *Optical Materials Day* at **Cranfield University** in April 2016 in conjunction with speakers from **Schott AG**, **Heraeus Quarzglas GmbH** and **Hellma Materials GmbH**. The event offered considerable depth of information about optical materials, particularly optical glass, and provided an overview of upcoming trends. Laboratory tours of Cranfield's Precision Engineering laboratories were also available on the day as well as table top displays from **H.V. Skan** and **Torr Scientific**.

April 2016

ASPE 2016 Spring Topical Meeting

Massachusetts, USA.

Jonathan Abir, PhD researcher at **Cranfield University**, had the opportunity to present his research *'Feedback based technique for improving dynamic performance of a small size machine tool'* at the *American Society for Precision Engineering (ASPE) 2016 Spring Topical Meeting: Precision Mechatronic System Design and Control*.

The event organised by **ASPE**, took place at the **Massachusetts Institute of Technology**, Cambridge, Massachusetts, USA in April 2016. This is the Society's 5th Topical Meeting in a series on the precision design and control of mechatronic systems. The meeting developed and promoted a broader understanding of the precision engineering principles of determinism for use in meeting the challenges posed by the design and control of high-performance mechatronic systems. It brought together specialists and practitioners from academia, industry, and government for the exchange of ideas and to identify topics of common concern for further research. Jonathan was also successful in securing a travel award from the **Institution of Engineering and Technology** to enable him to travel and present at the meeting.

May 2016

Ultra Precision Manufacturing Conference 2016

University of Cambridge, UK.

This annual event was organised and led by first year MRes students from the EPSRC Centre for Doctoral Training in Ultra Precision Engineering. The event showcased advances in ultra precision engineering in fields such as aerospace, medical devices, metrology, non-conventional processes and photonics.

The day was a great success with a wide variety of presentations from the Centre, the **National Physical Laboratory**, **Culham Centre for Fusion Energy**, **Airbus Defence and Space**, **STFC Rutherford Appleton Laboratory**, **Xaar plc**, **Carl Zeiss**, **Heriot Watt University** and **Coherent Inc**.

The Centre also had the opportunity to exhibit at the event alongside **Advanced Chemical Etching**, **Aerotech** and **Micro-Epsilon**.

Many thanks to all the students and staff within the EPSRC Centre for Doctoral Training who delivered this excellent event. The organisation team were Lily Delimata, Nadeem Gabbani, William Fowler, Katjana Lange and James Ryley at the **University of Cambridge**.

May 2016

National Manufacturing Debate

Cranfield University, UK.

The *7th National Manufacturing Debate* took place at **Cranfield University** in May 2016. Over the past 7 years, Cranfield has welcomed over 1,000 delegates to this event which have discussed key issues within the manufacturing sector.

This year's theme was *Accelerating UK Manufacturing Growth* and the keynote was given by the Business Minister Rt Hon Anna Soubry MP. The presenter of the Debate was Ben Wright, Political Correspondent at the **BBC**.

The EPSRC Centre in Ultra Precision joined other EPSRC Centres for Innovative Manufacturing as exhibitors at this event.

May 2016

Future Challenges of Instrumentation and Control in Ultra Precision Manufacturing

Renishaw plc, Gloucestershire, UK.

The Centre held this one day meeting in May 2016 at Renishaw plc, New Mills, Gloucestershire. The aim of this networking event was to bring the control and instrumentation communities together to discuss their particular challenges and advances, and consider how combining these strengths can build new ultra precision technologies.

Presenters on the day were from **Renishaw plc**, **Cranfield University**, **University of Cambridge**, **Aerotech Ltd**, **National Physical Laboratory** and the **EPSRC Centre for Innovative Manufacturing in Advanced Metrology** at the **University of Huddersfield**.

June 2016

euspen's 16th International Conference and Exhibition

University of Nottingham, UK.

The *16th International Conference and Exhibition of the European Society for Precision Engineering and Nanotechnology* was held at the **University of Nottingham**, UK.

The Centre had an exhibition booth at the conference and many of the PhD researchers from **Cranfield University** and the **University of Cambridge** had the opportunity to display posters during the poster sessions. PhD researchers Jason Ten and Tianqi Dong both won prizes in the poster sessions. PhD researchers Jonathan Abir and Adam Bennett from Cranfield gave oral presentations. Nan Yu, also from Cranfield won the Heidenhain Scholarship which subsidised his attendance at the conference. Centre Director Paul Morantz and Principal Investigator Prof Paul Shore both chaired oral sessions at the event.

June 2016

Laser FIB: Industrial Applications

University of Cambridge, UK.

The event was held in June 2016 at the Institute for Manufacturing (IfM), **University of Cambridge**, where the Centre's laser FIB platform is being developed. The event examined the applications this new platform can address for manufacturing up-scale and look to new innovations that will now be possible utilising the unique hybrid processing machine.

Speakers at the event were from the **University of Strathclyde**, **FEI**, **Carl Zeiss Microscopy GmbH**, **University of Cambridge**, **University College London** and the **University of Southampton**. Participants were able to view facilities on the day through a series of laboratory tours.

Event speakers

June 2016

Left to right: Prof Pat McKeown, Dr. Ir. Jelm Franse and Prof Paul Shore

Prestige Lecture

Cranfield University, UK.

2016's Prestige Lecture was presented by Dr. Ir. Jelme Franse of **ASML**, The Netherlands entitled *'Precision Mechanics and Mechatronics in Precision Mechanics and Mechatronics in Lithography Equipment – Key Drivers for the Continuation of Moore's Law for Semiconductor Devices'.*

The evening was a great success with participants attending from industry, academia and local schools and colleges. The lecture was led by Prof Paul Shore, FREng of the **National Physical Laboratory** and Prof Pat McKeown OBE, FREng provided the introductory presentation prior to the lecture.

September 2016

Precision Engineering Industrial Short Course

Cranfield University, UK.

The Centre held its annual *Precision Engineering Industrial Short Course* at **Cranfield University** 19-23 September 2016. This year delegates were welcomed from **Lockheed Martin** (USA), **Brazilian Synchrotron Light Laboratory** (Brazil), **FANUC UK Ltd**, **Aerotech Ltd**, **Power Photonic Ltd**, **Aselan Inc.** (Turkey) and **Tianjn University** (China).

Laboratory equipment demonstrations were provided by Centre community members **Micro-Epsilon** and **Aerotech Ltd**.

Martin O'Hara, the Centre's National Strategy Manager was active in attending various events throughout the duration of the National Strategy Programme in order to build the UK ultra precision network and to disseminate the activities of the Centre. These included: *NMI Industry Summit* (London), *UK Inertial Fusion Network Kick-Off Meeting* (London), *Hexagon Metrology Precision Centre Opening Event and Measurement Technology Workshops* (Milton Keynes), *Leading the Move from Diagnostics to BiognostiX* (Cambridge), *Photonics North West/Wales Seminar & Manufacturing Electronic Systems of the Future* (Daresbury), *Manufacturing for Plastic Electronics* (Cambridge), *Photonex 2013, 2014 and 2015* (Coventry), *Advanced Engineering UK* (Birmingham), *Precisiebeurs 2013* (Veldhoven, The Netherlands), *UK Plastic Electronics Research Conference* (Loughborough), *Micro and Nano Fabrication of Next Generation Technologies* (Rutherford Appleton Laboratory, Harlow), *Photonex Technology Roadshow* (Cambridge), *CERN Experiments in the UK: Meet the Buyer* (Royal College of Physicians, London), *Electronics Design Show* (Coventry), *Innovation in Large Area Electronics Conference (InnoLAE) 2015* (Cambridge), *Nikon Metrology Open Day* (Derby), *Thin Flexible Glass Exhibition and Open Day* (Kidlington), *National Electronics Week* (Birmingham), and *Micro Nano MEMS* (Birmingham).

October 2016

The Future of Precision Engineering

Academy of Medical Sciences, London, UK.

The Centre held its final outreach meeting *The Future of Precision Engineering* at the **Academy of Medical Sciences**, London in October 2016. The activities over the past 5 years were reviewed and the focus of the event was where precision and ultra precision manufacturing is heading. As well as the technologies of the processes and machinery that will be required to push ultra precision into being a mainstream production technology, the event looked to what future products this emerging high value manufacturing technology will enable. Speakers were invited from the **National Physical Laboratory**, **University of Cambridge**, **Cranfield University**, **DuPont Teijin Films UK Ltd**, **M-Solv Ltd**, **Gooch & Housego (UK) Ltd** and **Qioptiq**.

The afternoon discussion forum was led by the Centre's steering committee Chairman, Dr Paul Atherton of **Nanoventures Ltd** and commenced with an introductory talk by Prof Pat McKeown OBE, FREng and continued with active participation from the attendees on how they see the future of precision engineering.

Event speakers

The Centre visited and hosted industrial companies with the aim of forging collaborations, student sponsorships and participation at the Centre's outreach events. They included: **UK Manufacturing Accelerator** (Manchester), **Cranfield Precision** (Bedfordshire), **Carbonlite Converting Equipment** (Rochdale), **Timsons** (Northamptonshire), **M-Solv Ltd** (Oxfordshire), **Bosch Rexroth** (Cambridgeshire), **Hone-All Precision** (Bedfordshire), **Elektron Technology** (Cambridgeshire), **Lawrence Livermore National Laboratory** (California, USA), **Plasma Quest Ltd** (Hampshire), **Oxford Instruments Plasma Technology** (Bristol), **Abbey Precision** (Milton Keynes), **Double R Group** (Lancashire), **Enterprise Europe** (East of England), **ITL Vacuum Components** (Hastings), **DMP Aero** (Spain), **Lein Applied Diagnostics** (Reading), **Compound Photonics** (Newton Aycliffe), **National Physical Laboratory** (Teddington),

EPSRC Centre for Innovative Manufacturing in Liquid Metal Engineering (Brunel University, London), **Yamazaki Mazak UK Ltd** (Worcestershire), **Fronius UK** (Milton Keynes), **Citizen Machinery UK** (Bushey), **Seco Tools** (Warwickshire), **UK Fusion Advisory Board**, **RMIT University Melbourne** (Australia), **Osaka University** (Japan), **Renishaw plc** (Gloucestershire), **Innovate UK** (London), **Sandvik Tools** (Sweden), **AWE** (Berkshire), **DMG Mori** (Coventry), **Wave Optics** (Oxfordshire), **Sino-Bridge International** (China).

The Precision Engineering Institute at **Cranfield University** provided lab tours for VIPs Dr Maxine Mayhew, Group Commercial Director of **Northumbrian Water Group** and Iain Ferguson, the lead non-executive board member for the **Department for Environment Food & Rural Affairs** in March 2016. Dr Mayhew was appointed Council member at Cranfield University in 2016. In April 2016, the Centre welcomed Chris White, MP for Warwick and Leamington and Chair of the All Party Parliamentary Group in Manufacturing, who was on a tour of the facilities at Cranfield University.

Chris White MP (centre) with Prof Rajkumar Roy, Director of Manufacturing at Cranfield University (left) and the Centre's Director, Paul Morantz (right).

Educational Outreach

Martin O'Hara at Bedford School

Prof Paul Shore with staff and students of Vandyke School

School Engagements and Work Experience

Throughout the duration of the Centre, staff members were invited to various local schools to provide talks on precision engineering subjects and careers in engineering to a range of young learner ages (from pre-GCSE to A-level). Such visits included talks by Prof Paul Shore at **Vandyke Upper School**, **Kimberly STEM College** and **UTC Central Bedfordshire**. Martin O'Hara, the Centre's National Strategy Manager also engaged with local schools **Beauchamp Middle School** and **Bedford School**. These visits were on a relatively ad-hoc basis, although once a visit had been made it was usual for it to become an annual event, for example the *Samuel Whitbread Academy Careers Fair* attended annually by Dr Paul Comley.

Senior academics and researchers at the **University of Cambridge** gave talks to students at **Saffron Walden County High**, **Stationers' Crown Woods Academy**, **Lucy Cavendish College**, **Wellington Academy**, **Etonbury Academy**, **Frederick Bremer School** and the **University of the Third Age**. Over the past years, the **Institute for Manufacturing** at the **University of Cambridge** welcomed thousands of visitors, including students to the annual *Cambridge Science Festival* where presentations were made. The Centre has also hosted tours at Cranfield for local school **Samuel Whitbread Academy** and for the **London International Youth Science Forum**.

The Centre has also hosted work experience and internship placements at both campuses. An A-Level student from the **Sir Henry Floyd Grammar School** in Aylesbury spent a week at the Precision Engineering Institute at **Cranfield University** in February 2014 learning how to operate and programme milling, CMM and diamond turning machines. In June 2014, the Institute hosted a GCSE student from Bedfordshire's **Redborne Upper School** for a week who worked with the Watch it Made® team, undertaking a machine evaluation study as part of her work experience. The **Institute for Manufacturing** at the **University of Cambridge** hosted a student from **King Edward VII School**, Sheffield for a week working on the G3 marking laser to identify the correct parameters to produce a blue hue when marking a stainless steel substrate. They also welcomed two students from **The City Academy** based in Hackney who also worked with the G3 laser marker to try and obtain a parameter chart for colour marking on stainless steel.

Short Courses

Every September the Centre delivers the *Precision Engineering Industrial Short Course* aimed at engineers in the machine tool, automotive, aerospace, optics and semiconductor industries. Over the years, the course has attracted delegates from UK and overseas industrial companies and academic institutions such as **AWE**, **Cranfield Precision**, **Diamond Light**, **European Southern Observatory**, **FANUC UK**, **Aerotech Ltd**, **Professional Instruments Company** (USA), **Hembrug Machine Tools** (The Netherlands), **CERN** (Switzerland), **Ideko** (Spain), **NSK Ltd** (Japan), **The Manufacturing Technology Centre**, **SKF** (Sweden), **Holroyd Precision**, **Atlantic Diamond Ltd** (Ireland), **SIRIM Berhad** (Malaysia), **University of Strathclyde**, **Lockheed Martin** (USA), **Brazilian Synchrotron Light Laboratory** (Brazil), **Power Photonic Ltd, Aselan Inc.** (Turkey) and **Tianjin University** (China).

Company demonstrations are also held in the laboratories throughout the week the course takes place where delegates and campus staff and students are invited to partake. In the past the Centre has hosted laboratory demonstrations by **Actuance Scientific**, **Physik Instrumente**, **Armstrong Optical** and most recently by **Aerotech Ltd** and **Micro-Epsilon**.

"This course definitely built on my technical knowledge, enabling me to make a much better contribution to collaborative and customer projects at the MTC. A broad range of relevant machining topics was delivered at very high standards through intensive lectures and activities, to delegates from different engineering fields and interests. I am a Control Systems Engineer and had recently re-directed my professional career to the manufacturing sector. This course has raised my awareness on when control applications matter for precision machining processes and made me mindful that a good mechanical design should always come first."

Alejandra Matamoros from the **Manufacturing Technology Centre**, short course delegate 2015.

Short course lab demonstration by Mico-Epsilon

MSc Projects

As part of Cranfield University's Manufacturing and Materials MSc Programme, the Centre has sponsored group and individual projects for MSc students undertaking studies in manufacturing, materials and design related courses. Students spend 3 months working full time on group projects and 4-5 months on individual projects, many supported by industry. The students then partake in a presentation day, providing them with the opportunity to demonstrate they value they have brought to sponsoring clients as well as an opportunity for networking.

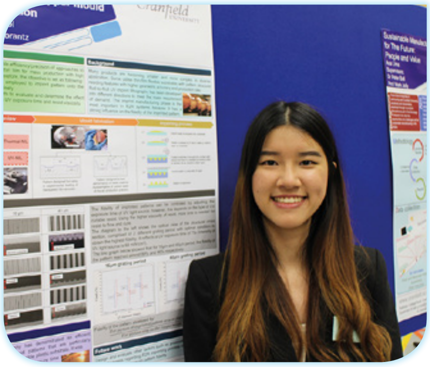
Sponsored group projects:

- *Development of an Ultra Precision Film Steering Test Facility*
  Betty Cabon, Sahil Chouhan, Amira T. El Araki, Miguel Camilleri, Maud Pfleger, Praveen Rao and Martyn Webber – 2013
  Watch the video here: https://www.youtube.com/watch?v=KzguWVLyTtQ

Development of an Ultra Precision Film Steering Test Facility Group Project Team, 2013

- *Design and Build of an Ultra Precision Diamond Machining System*
  Sammy Yassine, Quentin Bonnardel, Domenico Sinsicalco, George Zaganas and Hangtian Zhou – 2014
  Watch the video here: https://www.youtube.com/watch?v=ph4yYxQeItE
- *Watch it Made®*
  Florian Caroff, Armand Didier, Wei-Ting Hsu, Charles Langlais, Gabriel Meng and Tian Tan – 2014
  Watch the video here: https://www.youtube.com/watch?v=kNltngtmihl
- *Watch it Made® Go Mobile*
  Stephen Jadi, Julien Haba, Clotilde Lebrun, Ramóna Péter, Bich-Lan Phan, Bertrand Richer and Robbie Wang – 2015
  Watch the video here: https://www.youtube.com/watch?v=mrCxmVN3OWc
- *Roll to roll manufacturing of transparent conductive electrodes using Cu nanowires*
  Raffaele D'Addario, Adriana Karcz, Ansab Khalid, Luis Rubio García and Wei Wang – 2016

Sponsored individual projects:



Suphansa Lieotrakool, MSc in Engineering and Management of Manufacturing Systems

- *Assessment of the μFour Machine Based on the Processing of Complex Features*
  Oliviero Corinaldi – 2013
- *Dimensional Deviations of CLIC Standard Discs During Machining Operations*
  Bastien Moreau – 2013
- *Analysis of Diamond Turned Surfaces of CLIC Standard Discs*
  Cindy Potyrala – 2013
- *Ultra Precision Encoder Technology for Position Referencing*
  Kai Hollstein – 2015
- *Imprinting Lithography for Flexible Transparent Plastic Substrate by using Copper Mould in Mass Production*
  Suphansa Lieotrakool – 2015
- *An Approach to Smart Temperature Measurements on Advanced Materials for Optical Fabrication*
  Vicente Rivas Santos – 2015

eu**spen** Challenge

The **European Society for Precision Engineering and Nanotechnology** (eu**spen**) organise the *eu**spen** Challenge* on an annual basis. This is an international competition to identify outstanding students across Europe 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 newly acquired skills in a constantly changing and demanding market. Working in culturally diverse teams, the students benefit from national and international teamwork exposure, engineering and business skills development, influential professional network building and the unique opportunity to connect with companies in the field.

Centre PhD researchers have been successful over the past years in winning the UK national heats of the *eu**spen** Challenge*. Nan Yu and Jonathan Abir of **Cranfield University** and Karen Yu of the **University of Cambridge** were successful in winning a place at the *eu**spen** Challenge* in 2014, held at **Heidenhain GmbH**, Traunreut, Germany. Jonathan Abir was part of a winning team that year who were awarded the best presentation and most innovative solution. James Norman, PhD researcher at **Cranfield University**, got through to the national heats in 2015 and went on to participate in the *eu**spen** Challenge* in Sweden, 7-9 July 2015.

Jonathan Abir (right) at the eu**spen** Challenge 2014

Watch it Made® team with pupils of Cardinal Newman Catholic School, Luton, with Denis Chick, Director of Communications at Vauxhall Motors (left) and Dr Paul Comley of Cranfield University (right)

Educational Demonstrator Programme: Watch it Made®

Watch it Made® is the Centre's educational demonstrator programme conceived by **Cranfield University** staff Paul Shore and Paul Comley; a programme that would help raise public awareness and interest in precision engineering. After brainstorming sessions and interactions with local school children, the theme and focus for the educational programme was established.

Watch it Made® is about enthusing young learners into aspects of precision engineering by enabling them to produce their own high quality watch. They design and make the significant watch components themselves and then assemble it. This learning experience aims to give young people "pride of producing" a quality product.

While the scope of the programme was ambitious, it was considered in depth. With some 650,000 12 year old pupils in schools, a full roll-out across the UK would ultimately require Watch it Made® to become part of the school STEM curriculum. In recognition of this, the engagement of leading STEM programme advisors was secured via the established networks of the **Royal Academy of Engineering**. To achieve this goal, a number of industrial partners would need to be secured and the programme tested.

A local SME, **Fusing Creativity** was engaged to develop the branding and promotional material for the programme. The website **www.watchitmade.org** was created and the trade name was registered. A detailed project plan and costing for the national roll-out was developed during 2014.

An alternative delivery mechanism considered was to open retail shops as opposed to offering the watchmaking experience through schools. To advance the project, two Masters group projects at both Cranfield and Cambridge campuses were supervised by Paul Shore and Paul Comley in 2014. The group at Cambridge evaluated the proposed concept of Watch it Made® as an educational experience. The group project team at Cranfield defined the content of the Watch it Made® experience and designed a watch that could be produced by children. They also demonstrated the fun learning experience that children get when they use modern engineering design and manufacturing to make a self-designed quality watch.

Florian Caroff and Armand Didier were part of the **Cranfield University** MSc group project that defined the content of the Watch it Made® experience. For his Masters thesis Florian investigated and defined the modern machinery necessary for children to make watch components and Armand designed simple to use tooling that enables children to easily and safely assemble their own watch.

Following in depth research and evaluation, in 2014, Watch it Made® was set up in a dedicated manufacturing learning studio based at **Cranfield University**. Initially children spend time choosing their watch face dial and see how it is printed using UV inkjet technology. They then get hands on experience mounting their watch case in a precision lathe, operating it, and seeing their watch body machined. Thereafter, they personalise the watch rear cover using a micro-milling process. 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 workshop, all of the children leave with their own personalised timepiece.

At the end of their studies, Florian and Armand decided to further pursue the Watch it Made® activity and looked into launching a spin out company incubated within the EPSRC Centre for Innovative Manufacturing in Ultra Precision at **Cranfield University**.

Watch it Made® was launched at the *3rd Annual EPSRC Manufacturing the Future Conference* at the **Glasgow Science Centre** in September 2014. The first studio experiences were held in October 2014 to children of **Cranfield University** staff.

Funding secured through the EPSRC Impact Acceleration Account 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. The scheme is funded by the **Department**

Watch it Made® Go Mobile group project team with supervisor Dr Paul Comley and Cherie Denton, Community Relations Coordinator at Vauxhall Motors, Luton

for Business, Innovation and Skills, and supports projects across the UK that creatively engages the public with engineers.

Vauxhall Motors in Luton has supported Watch it Made® through sponsorship, initially loaning a vehicle for the MSc group project *Watch it Made® Go Mobile*, which researched the design, specifications and development techniques for a mobile experience, thus enabling Watch it Made® to be delivered outside of the studio. **Vauxhall Motors** also sponsored an experience for pupils of **Cardinal Newman Catholic School**, a school near to their Luton manufacturing site. Watch it Made® experiences were also sponsored by **Hexagon Metrology** in Milton Keynes and **Contour Fine Tooling** in Stevenage.

Experiences have also been delivered at the **Cambridge Science Festival** in March 2015 and at the **National Physical Laboratory** during October 2015 half term as part of the 60th anniversary of the atomic timekeeping. 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 in October, taking the opportunity to see the experiences being delivered and spoke with the pupils about their watchmaking experience.

The funding secured through the EPSRC Impact Acceleration Account, Ingenious and industrial sponsors has enabled Watch it Made® to host some 600 experiences for school aged children of staff from **Cranfield University**, **University of Cambridge** and **NPL** together with primary and secondary and secondary schools throughout Bedfordshire, Buckinghamshire, Northamptonshire and Hertfordshire. Schools included **Samuel Whitbread Academy**, **Arnold Academy**, **Goldington Academy**, **Bedford Modern School**, **Bushfield School**, **Hastingsbury Business and Enterprise College**, **Holywell School**, **Biddenham International School and 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**. Watch it Made® also welcomed a pupil from **Redborne Upper School and Community College** who was interested in pursuing a career in watchmaking and assisted him with the skills section of the bronze Duke of Edinburgh's Award he was pursuing.

A number of business plans have been developed and considered at **Cranfield University**. A contract is presently being negotiated

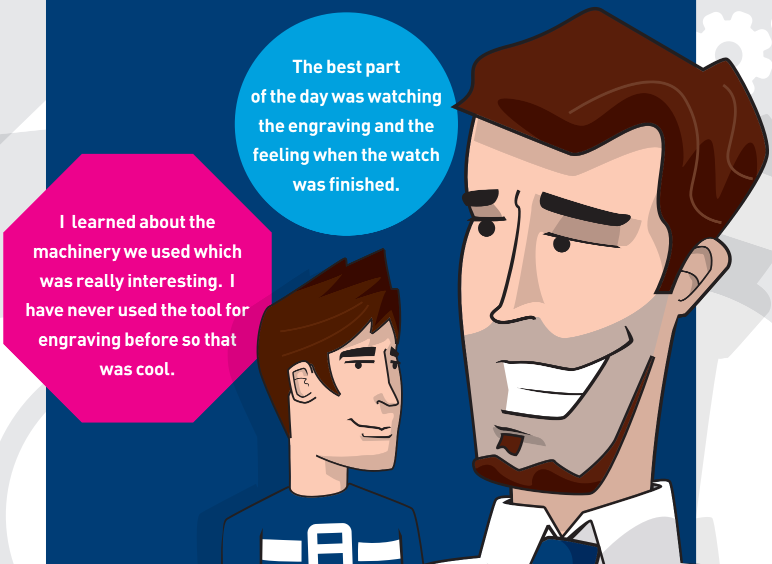
between **Cranfield University** and the **National Physical Laboratory** to enable the Watch it Made® activity to be further rolled out nationally by the Engineering Division at the **National Physical Laboratory**. Their plans are to use its engineering and science apprentices to deliver the experiences with the aim of engaging other innovation centres such as **HVM Catapults** in the national rollout process. At the time finding was granted by the **Royal Academy of Engineering**, Professor Paul Shore at **Cranfield University** became Head of Engineering Divisions at the **National Physical Laboratory**. He will facilitate the rollout and business development of the educational programme.

"I would like to say a big thank you on behalf of Hastingsbury. We had a fantastic time today making watches. All of the kids were buzzing in the mini bus on the way back. They could not wait to show their friends what they had made. At the end of the day some of the pupils came to see me and said "Thank you Miss for taking me today, it has really inspired me"."

Mrs Black, Lead Practitioner in Science, Hastingsbury Business and Enterprise College

"Our pupils thoroughly enjoyed the experience from start to finish. They were in awe of the intricate and complicated processes that went in to designing and manufacturing their own watches. It was great that they could personalise their own watch by engraving their names and date on the back; it was an experience they will never forget. A big thank you to all the staff at Watch it Made that made the visit possible."

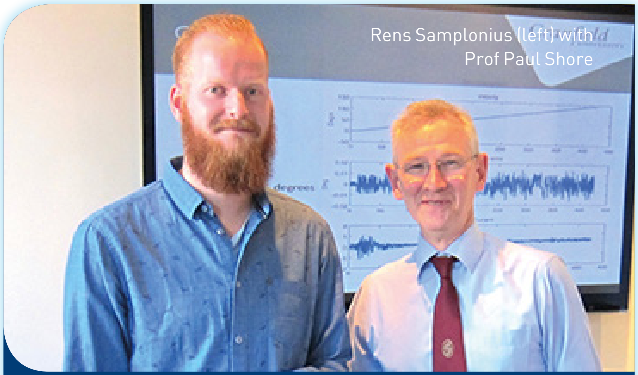
Amy Camfield, Head of Science, Goldington Academy



www.watchitmade.org

International Collaborations

The Centre hosted several researchers and academics undertaking internships and longer term research projects in conjunction with their home University or company.



Rens Samplonius (left) with Prof Paul Shore

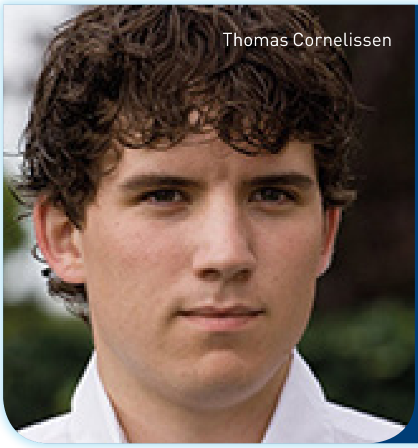
Rens Samplonius a MSc degree student of **Eindhoven University of Technology** spent three months at **Cranfield University** as an intern researcher working on the polishing of large optical components using a robot. The goal of this project was to enhance the existing industrial robotic polishing platform by fitting an additional rotary axis. The outcome of this project saw the successful design, assembly and control for the hydrostatic axis.

Yoshinori Takei

Visiting researcher **Yoshinori Takei** from the **University of Tokyo** undertook an international six month placement at **Cranfield University** in June 2014 to January 2015. He performed a detailed verification analysis of Cranfield's large mirror optical test measurement tower and his research was presented at the eu**spen** Special Interest Group Meeting on Structured and Freeform Surfaces, in November 2014 in Padua, Italy. These results were welcomed by UK company **Lambda Photometrics** who will use the data to validate the performance of interferometers they supply. After his return to Japan, Yoshinori San presented his Cranfield based research at the annual conference of the **Japanese Society for Precision Engineering (JSPE)**.

Dr Xiaofeng Zhang, lecturer in the School of Mechanical Engineering at **Tianjin University** in China is at **Cranfield University** for a year as a visiting academic researching the air bearing system in the reel to reel platform. Dr Zhang's research interests are the analysis and manufacture of air bearing systems, precision machine equipment development and brittle material machining.

Dr Xiaofeng Zhang



Thomas Cornelissen

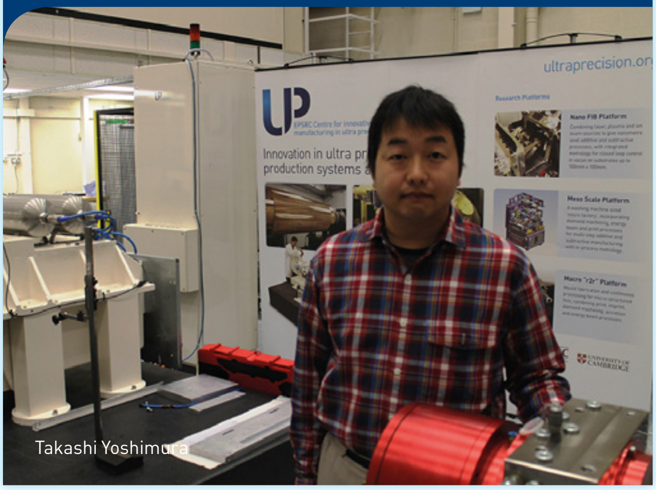
Thomas Cornelissen, a Masters student in Mechanical Engineering from **Eindhoven University of Technology** in The Netherlands undertook a project under the supervision of Paul Morantz at **Cranfield University** from October 2016 to February 2017 as part of the Erasmus Exchange Programme. For his internship, Thomas is following up on the work of PhD researcher Jonathan Abir on the XAC positioning module of the meso research platform to improve performance based on the Virtual Metrology Frame concept. He looked into improvements in terms of construction, sensor placement and model verification based on time-based measurements. Thomas also looked into items that were suggested for improvement and future work.

Additionally, the Centre for Industrial Photonics at the **University of Cambridge** hosted **Michal Strzelecki**, an Erasmus Exchange Programme student from the **Wroclaw University of Technology** in Poland for 3 months during the summer of 2015. He was responsible for the CD designs of housing structures to hold the various Aerotech drivers and electronics in the new ultra precision laser FIB platform.

Dr Lin Zhang

Dr Lin Zhang, Assistant Professor and Graduate Tutor at **Nanjing University of Aeronautics and Astronautics** in China, spent a year between 2015-2016 with the Precision Engineering Institute at **Cranfield University** undertaking research in ultra precision continuous film processing, which involved several key technologies including diamond ultra precision turning, electroless nickel coating technology, grating machining technology and the replication onto film using FIB tools.

Visiting academic **Takashi Yoshimura** of **NSK Ltd**, Japan also spent a year between 2015-2016 with the Precision Engineering Institute at **Cranfield University**. His research focused on the development of a reel to reel bearing system for the Centre's reel to reel platform. Takashi San has been working at **NSK Ltd**, a Japanese bearing manufacturer for over 10 years. His speciality is numerical analysis and he has designed grinding spindles for their bearing manufacturing processes.



Takashi Yoshimura

Prof Paul Shore visited China in August 2015 to present 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 (BISME)** to discuss the activities based on the memorandum of understanding in place with **Cranfield University**. The memorandum of understanding was signed in May 2014 during the *9th UK-China Workshop on Space Science and Technology*, also attended by PhD researcher Nan Yu. The collaboration will enable **BISME** and **Cranfield University** to define new methods and instruments for producing many advanced components required within future space systems.

Visiting researcher **Vincent Serantoni** from **The University of Montpellier** in France worked with the plasma figuring team at **Cranfield University** through the Erasmus Exchange Programme from March to August 2015. Working under the supervision of Dr Renaud Jourdain, his project work contributed to the preliminary stage of the design and control system for the plasma figuring facilities.

Dr Renaud Jourdain supervised a second visiting researcher through the Erasmus Exchange Programme from October to December 2016. **Andreas Wilde** is studying a Masters degree in Mechanical Engineering at the **Technical University of Munich** in Germany. His project at Cranfield University involves researching the development of a control system for a plasma delivery system to increase automation and stability.

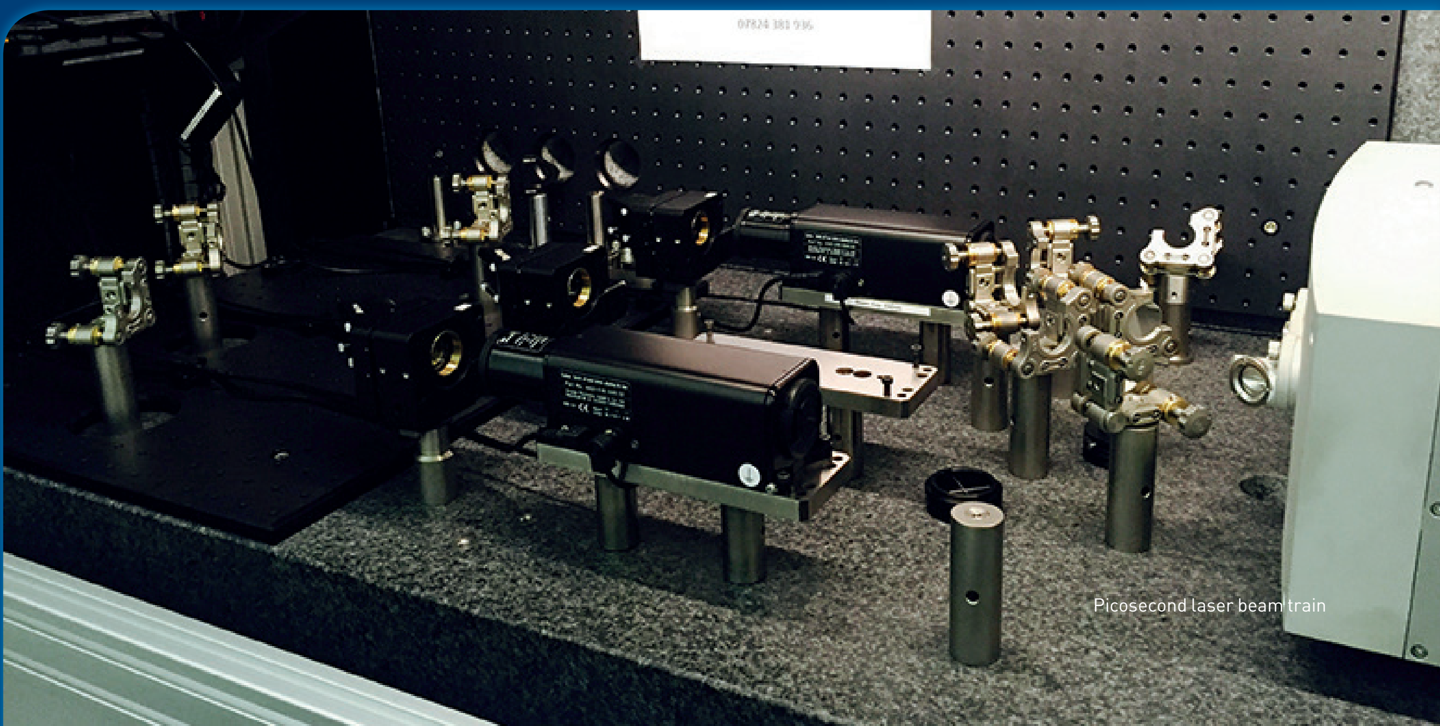
Andreas Wilde

Laser FIB Platform

The laser focused ion beam (FIB) platform has been 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.

Foundations of the Laser System

The laser platform consists of an integrated motion system that offers 5-axis positioning with a resolution of 25nm and positioning stability of 50nm. A complex optical beam train with picosecond laser and multi-wavelength capabilities at 1060nm, 532nm, 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 was completed in 2016 and has already been used for a number of process applications including microfluidic chip production, carbon nanotube fibre processing for field emission applications, thin film deposition of dielectrics and conductors and the patterning of graphene for electronic devices. The programme has delivered the detail design concepts, construction of a high resolution processing stage for the laser components and 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.

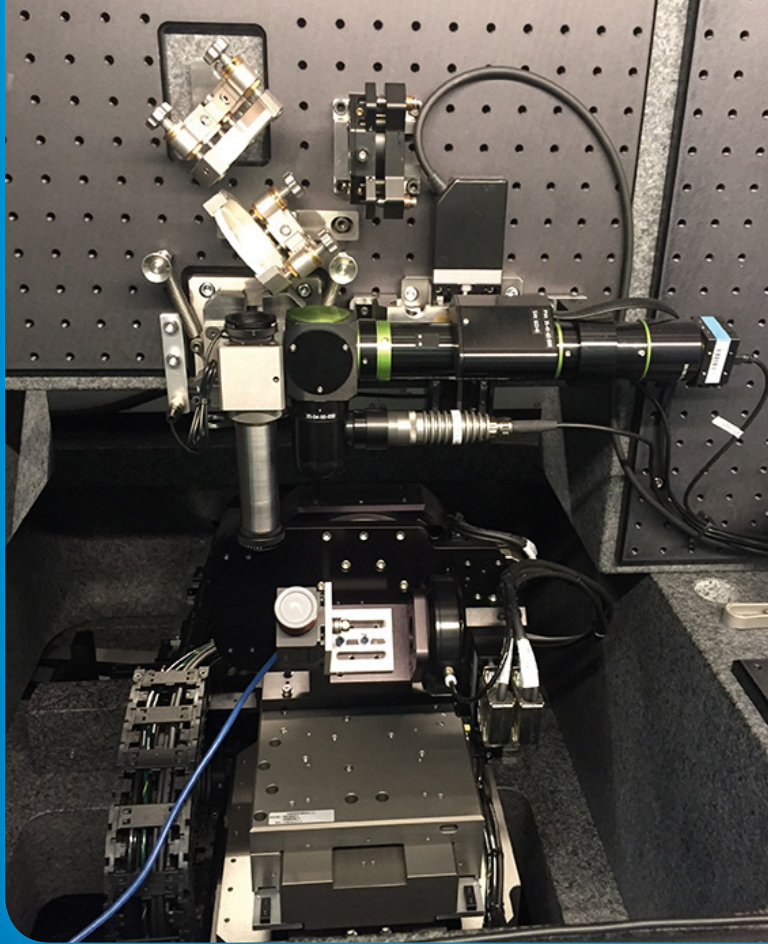


Picosecond laser beam train

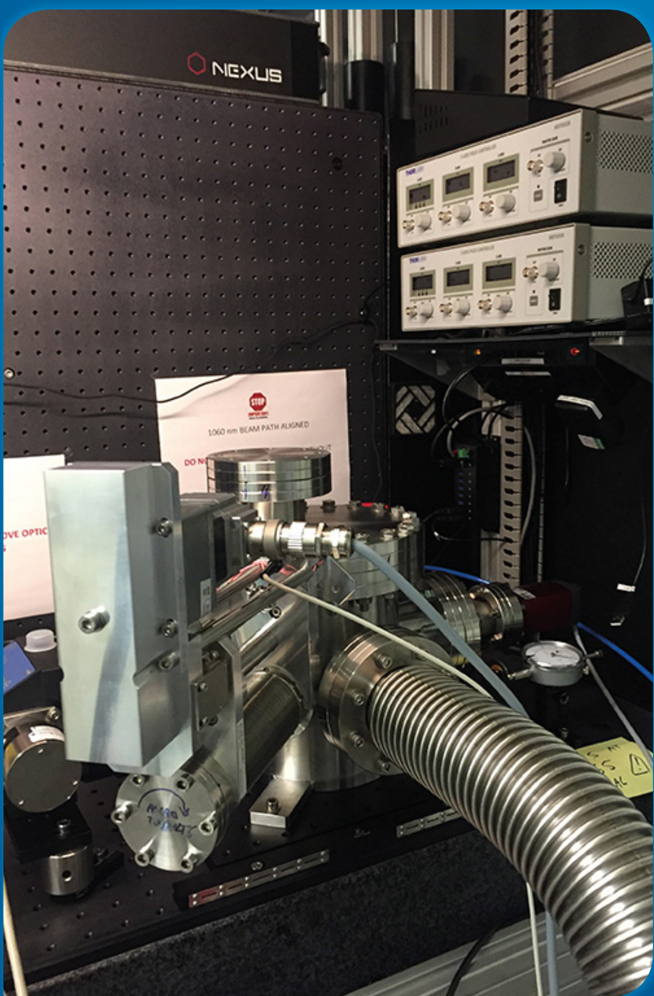
In Process Metrology

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, Digital Holographic Microscopy (DHM) generates in-situ 3-D data and Raman spectroscopy for the in-process validation of material composition and structure. The imaging techniques 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 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 a 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.

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 200nm using discrete ablation level control techniques that have been developed within the research portfolio programme. Future 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.



Ultra Precision Processing Stage

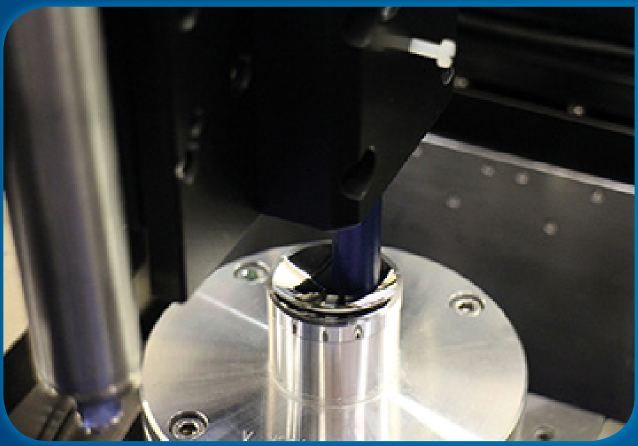


Ultra Precision Thin Film Coating System

Laser- FIB Process Chains

The combined processing steps of the laser system (resolution of ~200nm) 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 is 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 being applied in the final production stages of a number of MEMs related technologies including force sensors, and optical fibre clamping systems for high energy fibre arrays.

Measurement of germanium optic

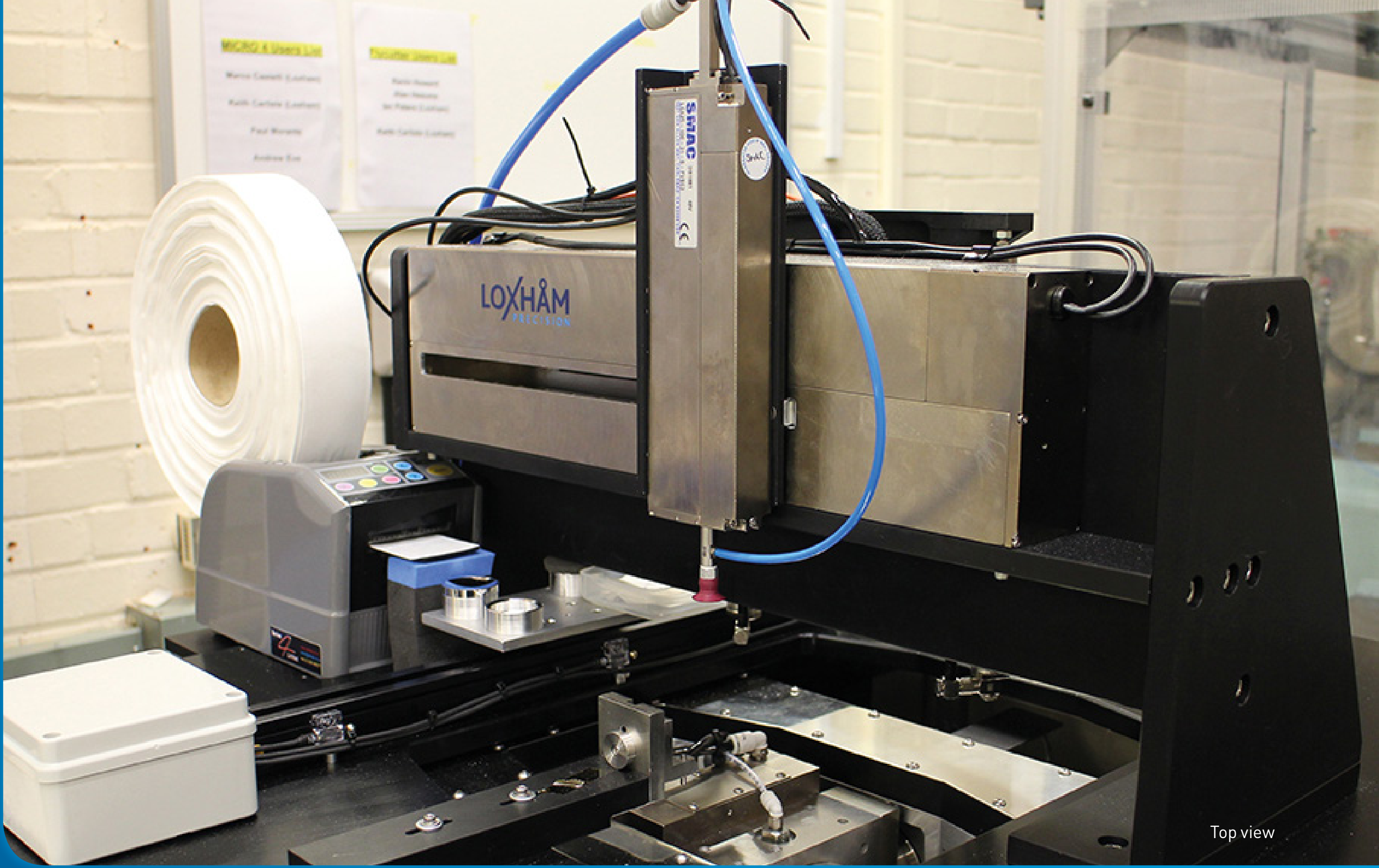


Meso Platform

The meso scale research platform programme has delivered an entirely new machine tool concept that is now being commercialised by a Cranfield University spin out **Loxham Precision Limited**. During the term of the Centre, the machine concept has formed a number of keynote presentations at both the European and the Asian Society for Precision Engineering and Nanotechnology (eu**spen** and ASPEN).

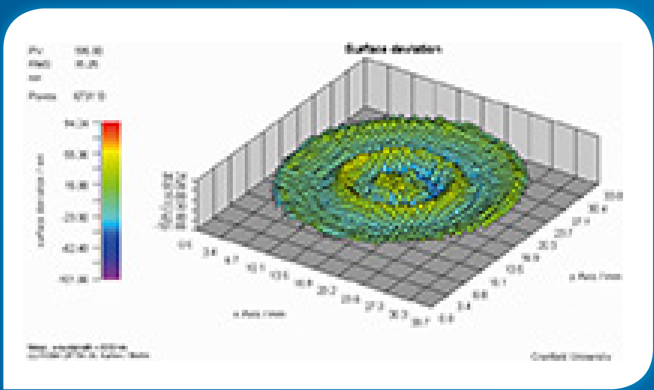
The early stage research performed by this ESPRC Centre has been critical to the realisation of this new machine tool concept. Fundamental modelling and testing of thermal and structural dynamics have enabled this highly integrated and compact machine tool to emerge with a competitive operating performance with a revised simpler design. Previous to this EPSRC Centre, other programmes contributed to the idea development and the building of prototype technical demonstrators. These included an EU Framework project and a separate project funded by the EPSRC Integrated Knowledge Centre in Ultra Precision and Structured Surfaces.

In addition, the Centre has aided the creation of a critical manufacturing capability in producing ultra-high accuracy linear slideways. This new capability for diamond machining large cubic components has been created through a Cranfield student group project. The group project video can be seen on the Centre's YouTube channel:
https://www.youtube.com/watch?v=ph4yYxQeItE



Top view

During the research that led to the meso platform, UK industrial interest was raised with regard to how this compact "domestic white goods sized" machine could be easily automated for effective fabrication of IR optics. Responding to an **Innovate UK** Automation programme, a new collaboration project was established and approved. This **Innovate UK** project has seen a specific 4 axes diamond turning meso scale research platform created. This machine was built by Loxham Precision in partnership with **Qioptiq Ltd**, **Aerotech UK** and **Hexagon Metrology**. The automation technology deals with workpiece loading/unloading/cleaning/centring/post process measurement. Techniques for automatically setting tool positions have also been created.



Form accuracy measurement from meso platform

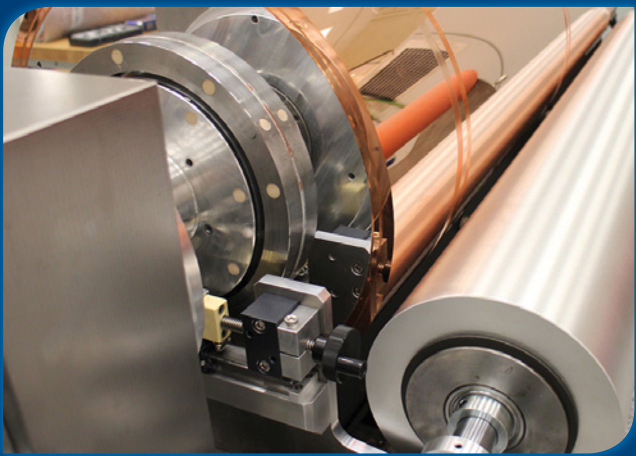
This **Innovate UK** project has also aided some simplification of the meso machine design by **Loxham Precision**. The commercial product is now easier and more cost effectively produced. The automation credentials of the meso platform concept have now been fully demonstrated and the performance of the machine in a 4 axes diamond turning variant format has been proven achieving <10 nm Ra roughness and λ/20 RMS form accuracy.

The meso scale research platform as a commercial product of **Loxham Precision Limited** has already secured a number of sales. Additionally, on-going performance trials are taking place with a number of UK and international companies.

The final delivered meso scale research platform is a 6 axes machine supplied by **Loxham Precision**. It provides the Centre with an ongoing UK designed and built ultra precision research facility having unique characteristics that afford a broad range of research avenues including complex shape component fabrication, 6 axes computer aided machining, low energy machine tool concept validation, micromachining, diamond turning and automated ultra precision fabrication. These research topics of interest to UK companies are in the fields of optics, compound semiconductors, MEMs, laser and instrument manufacture, inkjet print head fabrication, watch making and large science programmes.

Reel to Reel Platform

The reel to reel research platform has been created to provide unique UK research tools for advancing film production technology. This platform, which is at industrial scale having a 1.2 metre web capacity, is predominately built from specially designed and UK manufactured reel to reel machine tool sub-systems. The reel to reel research platform extends the UK infrastructure into production research of film based products.



Reel to reel research platform

Demonstrator test system created by a Cranfield MSc group project

It is significant that this large scale reel to reel research platform complements the unique **UPS²** micro structured roll fabrication facility which was previously established by the research team under the EPSRC Integrated Knowledge Centre in Ultra Precision and Structured Surfaces (UPS²).

The **UPS²** roll fabrication facility was spun out of **Cranfield University** in 2015. It now operates as **UPS² Limited** led by John Allsop who was previously the EPSRC **UPS²** business manager. **UPS²** has grown its international customer base and successfully delivers large structured rolls (up to 1.2 metre wide) from its north Wales based facility (see **www.ups2.co.uk**).

Prior to building the main reel to reel research platform a demonstrator test system was created. This test system showed the potential and the difficulties for reproducible lateral positioning of plastic film at micrometre levels of accuracy whilst also steering the film horizontally across the web handling system. This first system was built through a Cranfield MSc student group project with industrial support from control system supplier **Fanuc UK** and measuring encoder supplier **Heidenhain GB**.

Test results from this machine indicated the importance of appropriate film measuring systems. Initial measuring research was advanced by Kai Holstein an Erasmus MSc student at **Cranfield University**. His work and through a subsequent partnership with the **National Physical Laboratory** led to a new film measuring device being designed and built by NPL Instruments for application to the main reel to reel research platform.

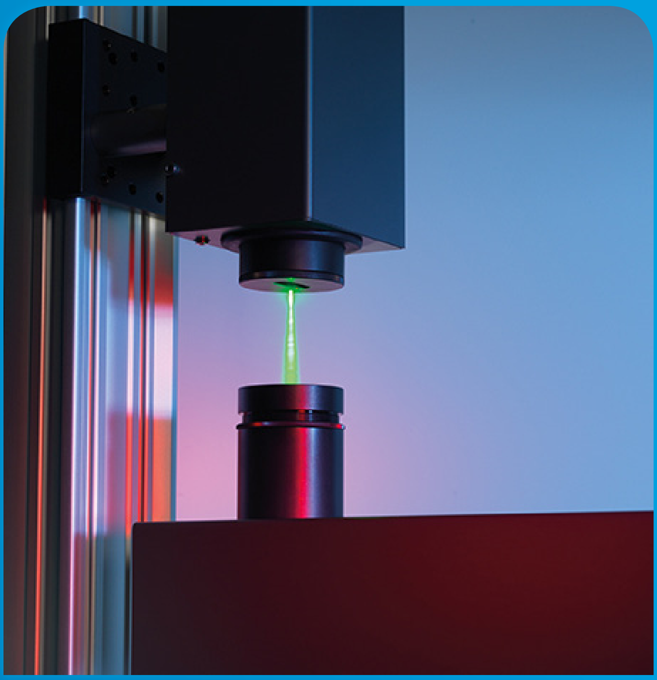
The main reel to reel research platform has been created through a number of linked research projects. These have delivered specific research capabilities and new knowledge that have resulted in the critical sub-systems that form the reel to reel platform.

High precision spindle technology has been advanced with regards to developing hard, resistant and yet machinable coatings for application to hydrostatic bearing components. This work took coating technologies from UK company **Poeton Ltd** and progressed ultra precision diamond machining to realise new UK designed and built hydrostatic spindles designs. These spindles employ high precision rotary encoder technology from UK company **Renishaw plc** working with high power density motor technology from **Etel** located in Switzerland. The created spindle design is of high precision, with low friction and mass and manufacturing cost. The high torque and integrated measuring technology presents optimum performance for controlling film position via large drums rotation.

It was recognised that large scale film position control at micrometre levels needed a more sophisticated control approach. The films are elastic and stretch during processing; they also distort through heat and deposition processes. Consequently, research was carried out regarding instrumenting films cheaply with measuring systems by deposition. Work at **UPS²** produced large scale drums having integrated encoders and the ability to replicate the encoders into the film was proved. This film processing methodology and the film measuring system developments performed at NPL have established a unique means to assess/control film position during reel to reel processing.

In order to construct rollers for film tension control and to provide alternative roll supporting spindles a partnership programme with **NSK** UK and Japan was established. **NSK** provided a senior researcher to work alongside the reel to reel team providing additional machine design and development support. Numerous tension control and roll on/off roller spindles were produced/acquired through this international research partnership.

To enable fine feature creation with high production rate, a highly controlled method to apply thin acrylic layers (and other polymers) to the film substrate has been established. Research and development activity with 2 UK SME's **Microsharp** and **iXscient**, led to a tendering process for a highly detailed slot die deposition technology. This tendering process led to the Centre working with **TE Troller** of Switzerland. This high specification slot die application system was devised, delivered and installed on the platform.



NPL measuring head device

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 any reel to reel system.
The quality of large micro-structured drums produced by UPS² 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. The NPL measurement technology for film evaluation is being discussed as a research topic in association with the new EPSRC Metrology Hub.

Grating roller

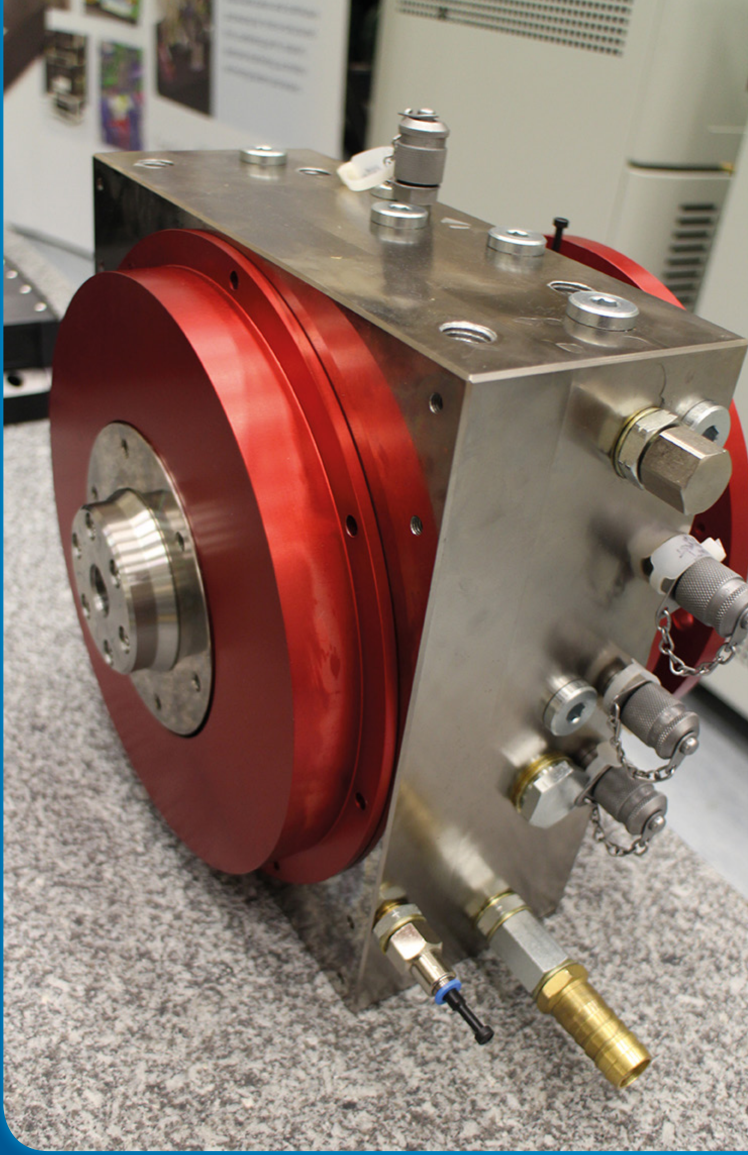
To polymerise the applied layers after slot die depositing and roll embossing it is necessary to expose the structured film to a short wavelength high intensity light. The Centre researched polymerisation with **iXscient**. Subsequently, new UV LED type systems were pioneered in partnership with UK company leading in this field; **UV Integration Limited**. A 20kW power 1.4 metre wide system was specified, developed and delivered by **UV Integration Limited**. This system is the largest **UV Integration** has produced to date.

In order to employ the high power UV illumination system on the reel to reel platform it was necessary to develop an effective temperature control unit. The Centre partnered with another UK SME, **3DE Limited**. They created a 24kW capacity high accuracy temperature control system for the UV light source. **3DE** also provided the temperature control and hydraulic system for the reel to reel platform hydrostatic bearings.

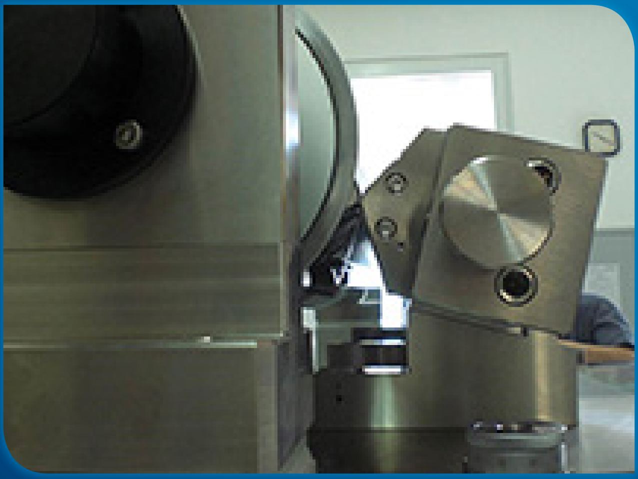
Sub-systems for film handling and roll-on and roll-off were designed and developed together with **Glyndŵr Innovations** the commercialisation arm of **Glyndŵr University**.

The above systems establish the reel to reel platform's passive film fabrication capability. A second part of the reel to reel platform is also being developed which provides an ability to inkjet print and laser machine films. This capability operates over the 1.2 metre wide films. This inkjet and laser machine capability has been developed together with UK company **M-Solv** who have provided both inkjet and laser units.

The reel to reel platform is being used by **Cranfield University** students engaged with the EPSRC Centre for Doctoral Training in Ultra Precision. It represents one of the world's most comprehensively equipped film processing research facilities created using significant UK expertise and manufacturing capacity. It will be the machine tool research basis of significant **EPSRC** and **Innovate UK** research in the area of passive and active film precision production research. Furthermore, the UK industrial engagement has stimulated a manufacturing supply chain in this emerging sector.



Hydrostatic spindle



Troller and roll off

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.

The projects are delivered by students at Canfield, Cambridge and Nottingham 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.

Microwave Generated Plasma for Ultra-Precision Fabrication of Optics

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

Plasma figuring using microwaves aims at providing highly efficient energy beams for rapid fabrication of optics. The chemical nature of this type of energy beam is targeted at silicon based materials. Thus far Adam has characterised a novel microwave generated plasma torch, which is operated at atmospheric pressure. The plasma torch is integrated into an existing plasma figuring system.[1] Argon and helium were used as carrier gases; sulphur hexafluoride and tetrafluoromethane were injected, in different ratios, as reactive gases. This plasma torch has been modified for optical material processing; in particular for the local surface correction of crystal quartz, which is a material of great interest in state-of-the-art optical systems, such as acousto-optic devices. This will be achieved by reducing the mid-spatial-frequency errors that are present on the surface of crystal quartz substrates. These mid-spatial-frequency errors - waviness, ripple errors, residual sub aperture tool footprints - are responsible for the scattering of light, at small angles, from the surface of the crystal quartz; thus resulting in optical hazing effects, photonic energy loss and pixel cross-talk, which limits the operating bandwidth and resolution of the optical systems.

The work conducted thus far has defined the design specifications of microwave plasma systems, detailed the design of a novel microwave plasma system (Figure 1), and a new high power system has been designed. Microwave characterisation (Figure 2) results, plasma plume characterisation by using Optical Emission Spectroscopy (OES) (Figure 3), and material removal characterisation by interferrometric measurements on substrates have been conducted.

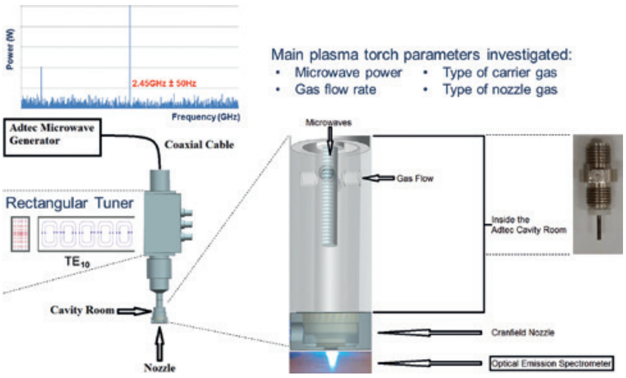


Figure 1: Experimental setup

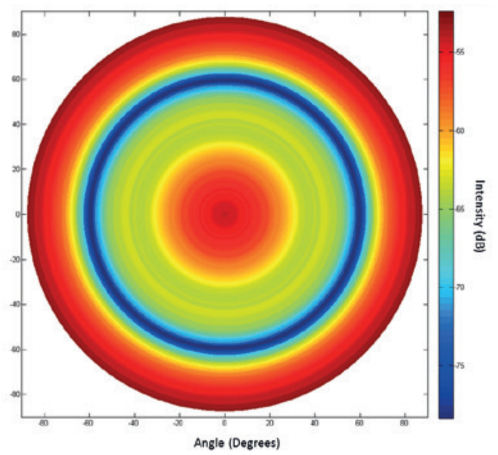


Figure 2: Microwave characterisation

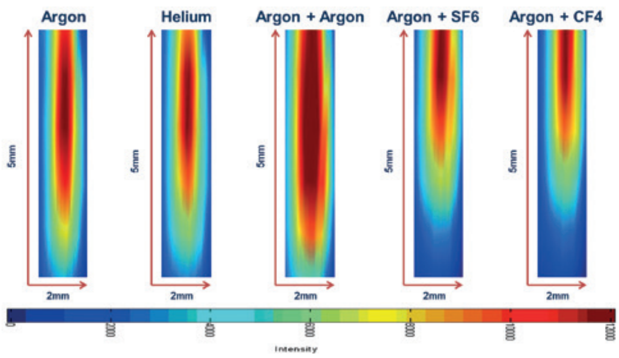


Figure 3: Optical Emission Spectroscopy characterisation on the plasma jet

References

[1] Bennett, A., Jourdain, R., Kirby, P., MacKay, P., Shore, P. Nicholls, J., Morantz, P. (2016). 'Microwave generated plasma figuring for ultra precision engineering of optics', 16th International Conference of the European Society for Precision Engineering and Nanotechnology, 30 May-3 June 2016, University of Nottingham, UK, 1, 269-70.

Multiple Beam Powder Bed Fusion Additive Manufacturing

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

Powder bed fusion (PBF) is one of several additive manufacturing technologies capable of building dense metal parts but due to its high build resolution PBF technology has captured the majority share of the metal additive manufacturing market. The technology has changed little in the ~30 years since its inception and it is still a relatively slow manufacturing technique despite constant incremental refinements to the process.

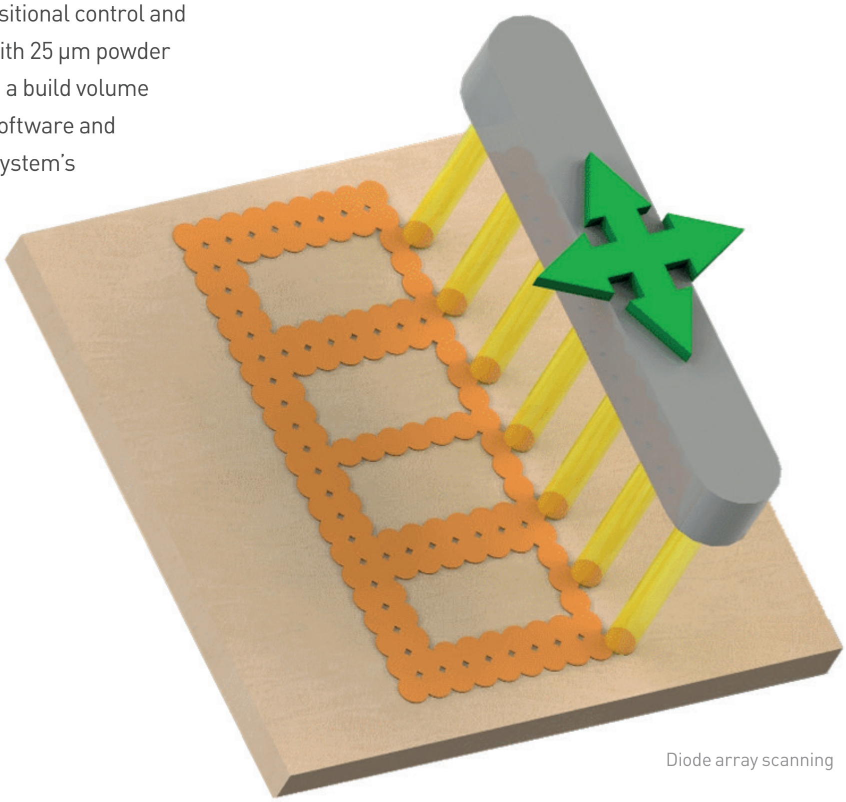
The build rate of a PBF machine is, in part, dictated by the power available to melt the powdered material. However every build material has a lower and upper limit to the useful amount of processing power per focal spot area, which means that to increase the build rate by increasing the available power requires the use of multiple energy beams each with a useful amount of power.

The objective of this research was to develop a multiple beam variant of a PBF additive manufacturing system. The design concept employed multiple laser diodes fibre coupled to an optical head that would be scanned across the powder bed by a gantry system. This is a scalable concept with a build rate proportional to the number of beams used. The work for this project fell into two parts; that of designing and building the system and that of characterising and evaluating the interaction of metallic powders with the multiple laser diode beams.

The system built for this research comprised seven 40 W diode lasers centred at 974 nm, 3 axis positional control and a fully automated powder handling unit with 25 µm powder thickness steps, atmospheric control and a build volume of diameter 100 by 70 mm high. Various software and firmware were developed to control the system's subcomponents and to allow objects to be built from STL files or by using images as patterns for prismatic objects.

In usage this technology builds objects by the sequential addition of voxels of consolidated powder so the creation of individual voxels was characterised along with elementary line and plane shapes. To build planar objects a scanning strategy is required and several were formulated for the optimum movement of a multiple beam optical head over a powder bed. The role of power was found to be critical for the wetting of the melt to avoid balling and the penetration of the melt into the previous layer to increase consolidation. With the 40W power available the ensuing balling created high spots within each layer requiring a minimum layer thickness of >300 µm to avoid the re-layering mechanism fouling on the part which gave a maximum relative density of 54% for solid parts.

This project has served as a successful proof of concept technology study and a flexible system has been built around the core concept. More powerful laser diodes are all that is needed to take this work forward towards producing higher density fully consolidated three dimensional parts. As a result of this work a U.S. patent application serial number 62/173.541 has been filed.

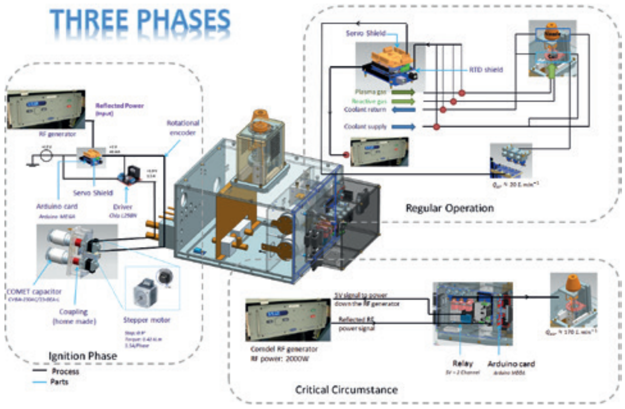


Diode array scanning

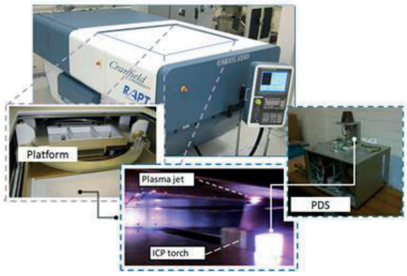
Control System for Plasma Figuring for Ultra Precision Surfaces

Hui Zhou

Hui Zhou's Masters by Research project focused on a unique control system for the plasma system used on a computer numerically controlled (CNC) machine tool. In the context of ever-increasing dimensions of optical components, there is a need for improving the robustness and securing the performance of the unique Plasma Delivery System (PDS) available at **Cranfield University**. The current PDS is based on an inductive output L-type radio frequency (RF) circuit, Inductively Coupled Plasma (ICP) torch and CNC motion system. The combination of optical component surface dimensions and the material removal rate of the plasma jet led to significant processing duration.



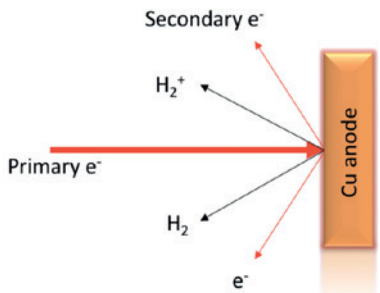
Based on the existing PDS for the unique plasma figuring machine Helios1200, Hui Zhou designed an enhanced PDS version. The novel design was given the capability to detect phases and automatically tune the impedance of the electrical load. The novel control capability was aimed at securing the process determinism, assisting the machine operator and monitoring crucial processing parameters.



Anode Materials for High Power Microwave Devices

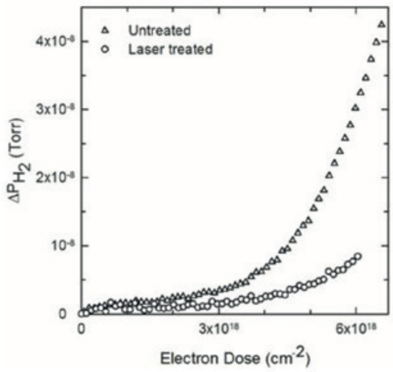
Daniel Gortat | Email: dg458@cam.ac.uk

Metal anodes in High Pulsed Power Electromagnetic (HPEM) devices erode during usage, limiting the lowest achievable pressure in a HPEM device reducing its efficiency. The challenges lie with the anode's significant contribution to outgassing, predominantly of the hydrogen atoms stored in its bulk and plasma formation, caused by the near surface ionization of the outgassed neutral atoms by the desorbed electrons or secondary electrons emitted from the anode – both 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.

Laser surface melting showed promise in reducing the outgassing in metals. The results exhibit a reduction in outgassing, by approximately a factor of four compared to that from untreated stainless steel. This is attributed to a reduction in the number of grain boundaries which serve as trapping sites for hydrogen in stainless steel. Such laser treated metals do not require post-processing to preserve the benefits of the treatment and are excellent candidates for use in high pulsed power electromagnetic devices.



Outgassing results showing the change in H2 partial pressure with 50 keV electron dose during 60 second electron irradiation.

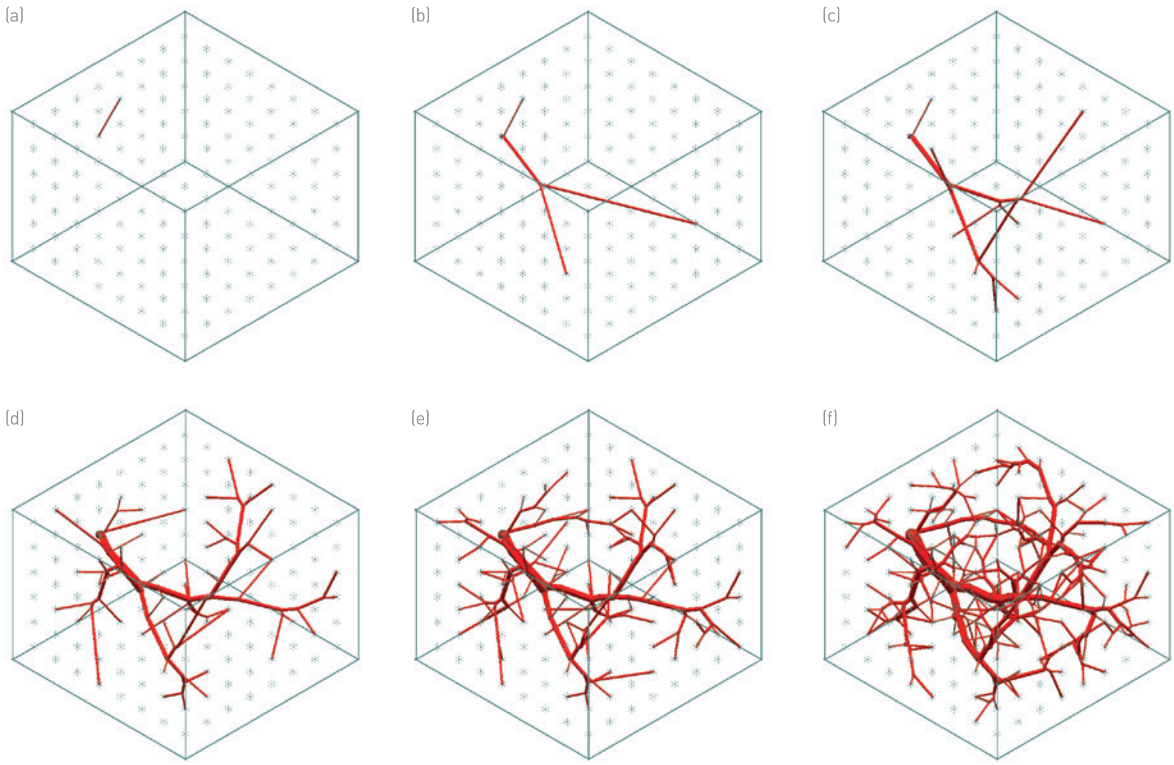
Design, Fabrication and Characterisation of Hierarchical Branching Vascular Networks

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

Development of engineered artificial tissue has diverse potential applications such as the generation of artificial organs for implantation and other research purposes. A current limitation in tissue engineering research is the poor vascularization in thick tissue. The establishment of a functional and hierarchical microvascular network is essential to ensure a proper mass transport (nutrients and waste) within the tissue. Inkjet 3D printing is a versatile method for the fabrication of such networks, as it allows reproducibility of the vascular structures as well as compatibility with the materials chosen for this purpose.

The first year of the PhD project involved the development of a method to create realistic and physiologically accurate branching vascular networks in a format that is 3D printer-friendly. To achieve this, an algorithm was created and programmed, based on existing computational models for the biosimulation of arterial tree growth. In the algorithm, a three-dimensional shape is defined, and the volume is divided into sub-units, which represent clusters of cells. The sub-units are represented by points in the 3D space (see image). A vascular tree grows by connecting a new random point in the space to the existing tree structure and recalculating the physiological parameters of every tree branch. Two independent trees grow simultaneously and are connected at the chosen points to create the network. Current work involves solving the problem of collisions between the two trees and improvement of the algorithm to obtain more realistic network distribution and morphology.

Future stages of the project will have focus on Computer Fluid Dynamic (CFD) analysis of the flow in the micro-vascular networks, as well as experimental fabrication and analysis of the fabricated vascular models.



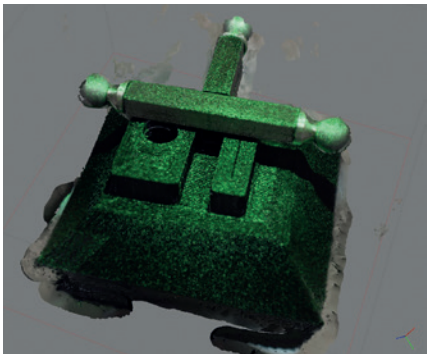
Arterial tree at different stages of growth. a) 1 cell. b) 3 cells. c) 10 cells. d) 50 cells. e) 100 cells. f) 250 cells.

Development of Camera Based Systems for Micro-Coordinate Metrology

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

Photogrammetry is defined as the science of measurement through the use of photographs. Stereo photogrammetry is one of the most commonly used techniques and involves the triangulation of common points between two images. The simplicity of photogrammetry has meant that it has been used as a method of measurement since photography was invented in the 1830s. For the first fifty years, photogrammetry was mainly used by architects as a fast and easy method of measuring buildings. It was not until the rise of digital computers that stereo photogrammetry could truly be considered for accurate close range measurements. The potential of stereo photogrammetry was now only limited by the models and imaging process used. As a result, research into reconstruction and calibration algorithms flourished, giving rise to the modern methods seen today. The recent advancements in digital photography have also been significant. Through careful calibration and the correct equipment, the 3D digitisation of sub-millimetre object features to a measurement uncertainty of a few micrometres is possible.

Over the first year of the project, work has been concentrated on developing a photogrammetry system that can then be used as a framework for any later developments that will be made. Another significant aspect of the work in the first year has been on determining a standard verification process that would allow any further developments to the system to be effectively compared. With all this in mind the original system was developed using a simple low-cost, high-resolution consumer DSLR camera and rotating table. This simple system allowed a dynamic range of camera positions and orientations to be tested and different magnifications. Further adaptations to the system were however required in order for the verification tests to take place. The VDI/VDE standards outline some basic tests to determine the accuracy that require spheres and ball bars with a surface roughness at least four times less than the anticipated system uncertainty. Given that the target uncertainty is on the order of a few micrometres, very smooth artefacts are required for system verification. A consequence of such a smooth surface is the loss in texture that is required in order to determine matches between images for triangulation. In order to combat this, a laser speckle texture projection system was fitted to the turntable in order to project a stationary pattern onto the sample surface throughout a scan. This process has allowed very smooth surfaces to be measured that would otherwise be invisible to the system. An example of a ball bar scan can be seen below.



Control System for Ultra Precision Processing

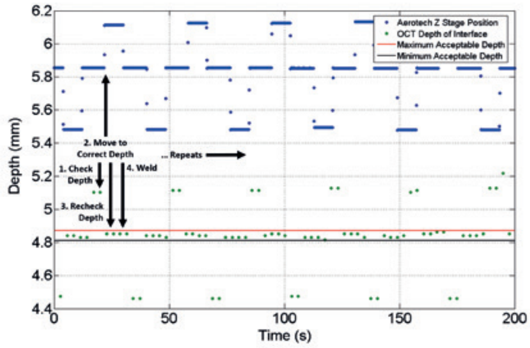
Karen Yu

High precision manufacturing of nano- and micro-sized objects has become the focus of industrial research due to a need to cram ever more into smaller devices. From smart phones to glucose monitors, today's technologies are entrenched within the ideals of miniaturization, resulting in high precision manufacturing as a dominant market force.

Traditional macro-manufacturing (≥ 10 μm parts and features) use closed loop monitoring and feedback to detect errors and correct them during processing, resulting in lower production defects. However, this is much more difficult to accomplish on the micro- and nanoscales. To this end, the goal of this project is to create a closed loop system capable of delivering high-precision laser processing for rapid micro- and nano-production.

Two metrologies systems, optical coherence tomography (OCT) and digital holographic microscopy (DHM), will be used to provide in-situ inspection and feedback. The system also features a nanometre precision 5-axis stage and various other monitoring to maintain beam alignment and consistency (e.g. average power, beam shape). Four different processing wavelengths (355 nm, 532 nm, 1030 nm, and 1064 nm), two different pulse durations (< 15 ps and 300 fs), and a variable repetition rate from single pulse to 2 MHz are available to process most materials. This project also represents the first part of the Precision Laser FIB Platform, responsible for bulk removal and characterization before final finishing with a FIB.

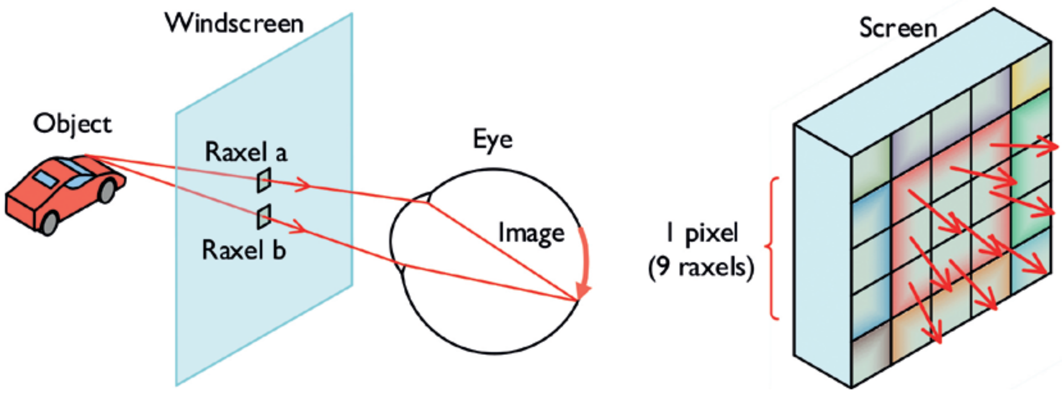
Glass-glass welding was chosen as a test application to demonstrate the capabilities of the system. Here, OCT was able to successfully identify whether or not the weld was successful. Also, during processing, the imaging system provided real-time data of the laser focal depth relative to the glass-glass interface, allowing the platform to correct for any deviations. The figure shows the positional information during processing of a sample that has a tilt applied (i.e. differing processing laser focus position from spot weld to spot weld), which the system automatically corrects for.



In-situ depth control data for glass welding

Jaguar Land Rover iHUD

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



A 3D, full screen, colour, heads-up display for automated augmented reality.

The market for augmented reality (AR) devices is expected to exceed $100 billion by 2020, but there are only limited commercial AR products currently available. Additionally there are very few market-ready technologies able to deliver a large area, 3D, AR user experience, and none suitable for challenging environments (automotive heads-up displays), or physically constrained devices (wearable technology). This project is investigating the shortcomings of current 3D technologies, and developing a display for use in consumer automotive windscreens. Automotive AR use cases include assistive safety warnings (road edge indicators, breaking distance markers, highlighting hazards), navigation directions (line follow, turn-by-turn), and contextual information (parking, petrol stations).

The technology proposed in this project is a light field display, where the angle and position of emitted rays of light are controlled, enabling a 3D image to be generated.

Light is coupled into a glass screen from the edge, and propagates through by total internal reflection. Using a layer with clusters of raxels (ray-pixels), light can be coupled out of the device and along a predefined ray. By controlling light intensity and the active raxels, a light field can be constructed.

Potentially this light field display eliminates the nausea, visual fatigue, and low depth accuracy caused by current 3D technologies, which would be unfeasible for an automotive display. A major advantage of the architecture however is no projector is required, reducing volume and allowing for space constrained displays such as wearable glasses, and automotive side windows.

Single pixel demonstrators are currently being studied, and the raxel layer is being optimised for efficiency, image quality, and manufacturability. Schemes to dynamically control raxel angle are also under investigation. A small proof of concept prototype display is being planned.

Thermal Analysis of Energy Beam Using De-Laval Nozzle in Plasma Figuring Process

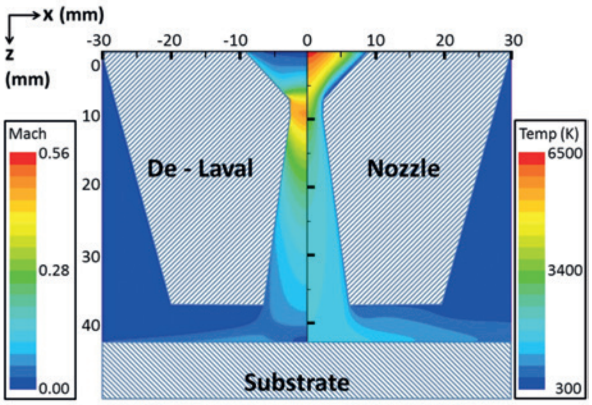
Nan Yu

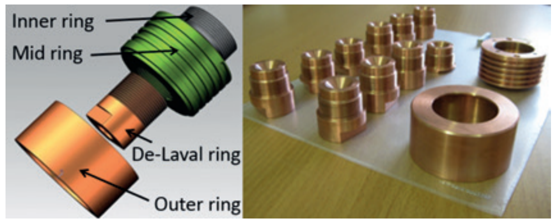
Plasma figuring was proven to be an alternative solution for the fabrication of large scale ultra-precise optical surfaces. The process was exceptionally rapid but residual errors were observed. The thesis written as a result of this research project addresses this issue by proposing an enhanced tool that provides a highly collimated plasma jet.

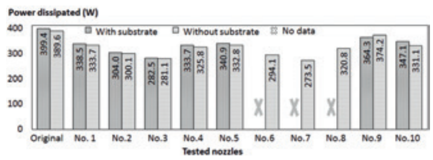
The enhanced tool is characterized by a targeted material removal footprint in the range 1 to 5 mm FWHM. The energy beam is provided by an Inductively Coupled Plasma (ICP) torch equipped with a De-Laval nozzle. The thesis focuses on characterization and optimisation of the bespoke plasma torch and its plasma jet. Two research investigations were carried out using both numerical and experimental approaches.

A novel CFD model was created to analyse and understand the behaviour of high temperature gas in the De-Laval nozzle. The numerical approach that was based on appropriate profiles of temperature and velocity applied on the nozzle inlet, led to a significant reduction of computational resources. This model enabled the investigation of the aerodynamic phenomena observed from the nozzle inlet up to the processed surface. Design rules and the effect of changing nozzle parameters were identified. Sensitivity analysis highlighted that the throat diameter is the most critical parameter.

A challenging power dissipation analysis of the plasma torch was carried out. Temperature and flow rate in key components of the torch were measured. Experimental results enabled the calculation of the power dissipation values for RF power up to 800 W and for the entire series of designed nozzles. This work enabled one to scientifically understand the power dissipation mechanism in the bespoke ICP torches. In addition, by comparing the intensity of the power dissipation values, one nozzle was clearly identified as being more capable to provide a highly efficient plasma jet.







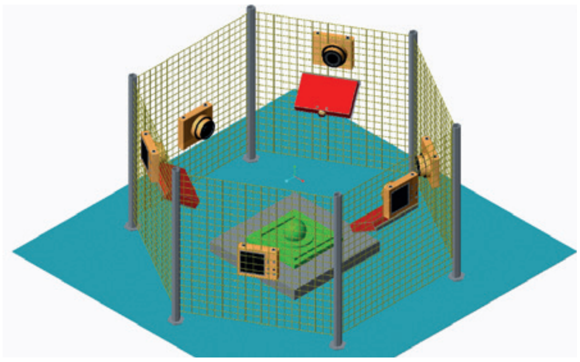
Development of Non-Contact Methods for Measuring the Outside Geometry of AM Parts

Patrick Bointon | Email: Patrick.Bointon@nottingham.ac.uk | Sponsor: Science and Technology Facilities Council

Project Overview

Metrology is an important tool 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 AM, a new and more flexible system needs to be developed. Optical measurement systems show considerable promise and so the aim of this PhD project is to develop and utilise coded structured light techniques (in particular fringe projection) in a new system for measuring the complex form on AM parts. The new system will be designed to be capable of measurement volumes of a cube of up to 750 mm sides to accuracies approaching 5 μm. The measurements will aim to be more intelligent and complete by utilising the untapped plethora of a-priori information, a concept we have coined information rich metrology (IRM).

Example of an aerospace additively manufactured printed part by 3T RPD.



A 3D CAD representation of the proposed multiple camera and projection, fringe projection system.

Current Research

The first year of this PhD focussed on performing an extensive literature review of the different optical techniques, highlighting the strengths and weaknesses of each. From this review, fringe projection (FP) has been identified as a highly promising measurement technique, and so the focus has been on developing a fully functional FP system to enable further investigation into IRM application in optical metrology. This work is currently looking at analysing the STL data from the CAD file in order to identify key features on the surface of the part to be scanned. This will allow us to tailor our measurements to each individual part in order to achieve to get a more complete scan, avoiding lots of occlusions and data missing.

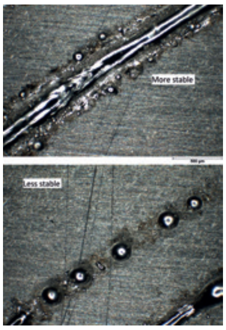
Novel Energy Delivery Techniques for Laser Additive Manufacturing from Metal Powders

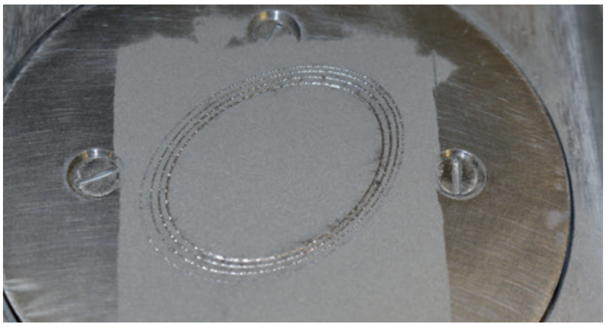
Jon Parkins | Sponsor: The Worshipful Company of Engineers

Current state-of-the art additive manufacturing machines are capable of producing any geometry from metal powders with <100 µm feature size and around 5 µm accuracy with great design freedom. However, these machines are essentially large prototyping machines; they are not optimised for mass production of single parts. In the biomedical industry, a mass produced additively manufactured part is the acetabular shell, part of the hip joint with a highly complex geometric structure. The current state-of-the-art manufacturing machines cannot supply enough parts to meet the demand for prosthetics. This project aims to determine the limitations of the existing process and identify new energy delivery methods to increase the throughput of laser melted parts.

Thermal gradients are one of the key limiting factors in laser additive manufacturing. Steep thermal gradients lead to localised shrinkage of parts during cooling. This results in large residual stresses in manufactured parts which can bend and crack the parts leading to failure. In-process thermal gradients in the liquid metal pool are likely key drivers of instability due to altered surface tension. It is hoped that reducing thermal gradients will improve melt performance and extend the available parameter space with larger beams and faster scanning. Heat delocalisation is being explored via several energy delivery mechanisms which it is hoped will be implemented into a new dedicated production machine for acetabular shells.

The outcomes of this project have led to development of new strategies enabling significant increases in material deposition rate in a scanning regime, and methods of implementation have been proposed. Feasibility studies on disruptive technologies have also been performed, which will form the basis of further research by subsequent students.





Diamond Machinable Coatings for Reel to Reel Platform

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

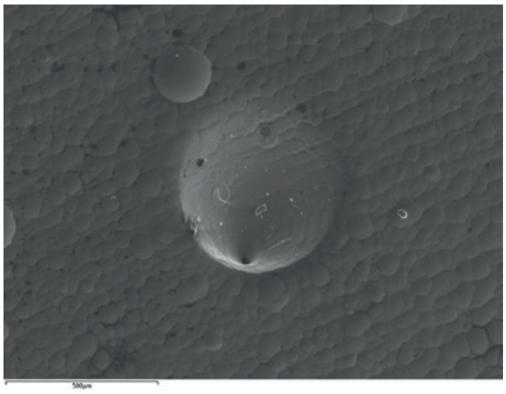
The purpose of this project is to recommend modifications and improvements (or an alternative) to the current processing route for optical quality wear resistant diamond turned coatings on ultra-precision manufactured rollers and hydrostatic bearings. In doing so, there is a need to create a common language and unified understanding of what "quality" actually means for this application between the manufacturer and consumer, regarding 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 ten 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 before 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 regarding the adhesion of the subsequent nickel coating, its smoothness, and the pitting rate.

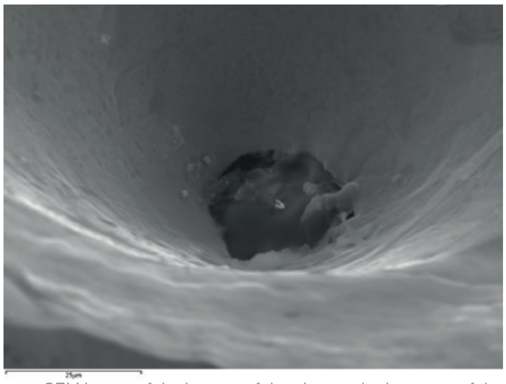
The project consists of identifying the current coating process issue, common problem towards the coating quality, and the specific aspect regarding the diamond machinability. The major concern was the coating surface finish and its effect towards to the diamond turning performance.

The project concentrated on the replication of a commercial production grade coating over aluminium testing coupons. Investigation of substrate preparation and its effect towards the final coating condition was carried out. Plating solutions from different sources were used for coating quality comparison. Samples from UK leading plating manufacturers are undergoing examination and feature registration.

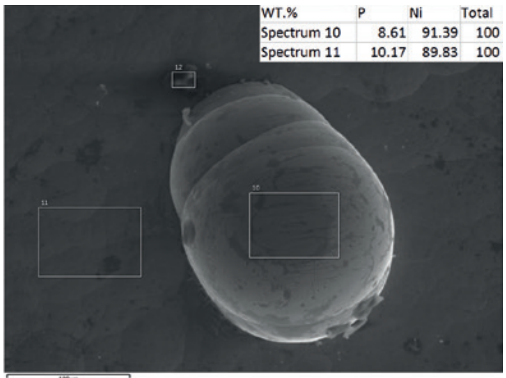
The next stage is to complete the detailed inspection procedure from existing ISO and ASTM standard, and produce a grading system targeting various aspects of the electroless nickel coating for diamond turning applications. It is possible to demonstrate the physical evidence of significant individual defects, and the effect of different defects on the diamond turning process.



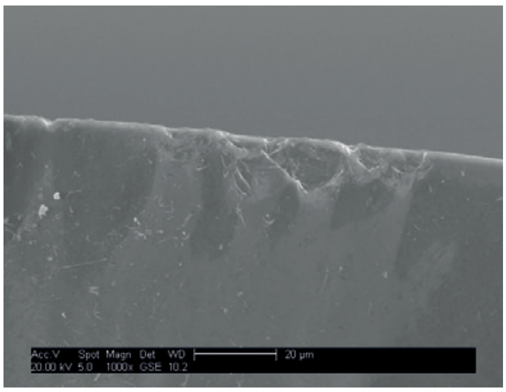
Example SEM image of a large pit in industrial sample coating.



SEM image of the bottom of the pit reveals the cause of the comet tail shaped pitting.



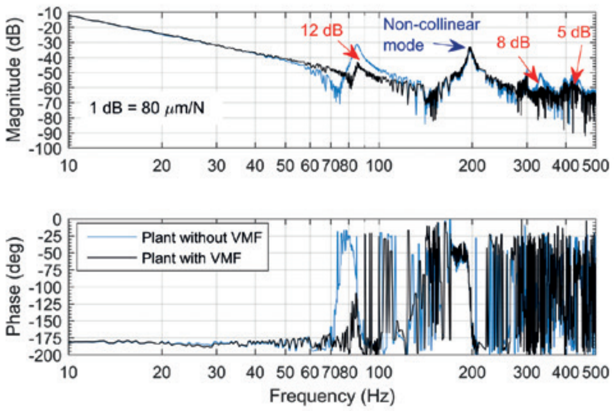
EDX analysis of a large bulge (spectrum10) over the surface of the coating with near 2wt.% difference in phosphorous content compared to the surface (spectrum 11).

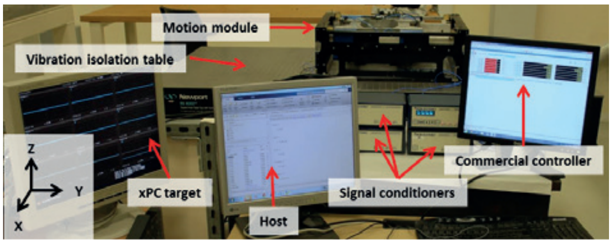


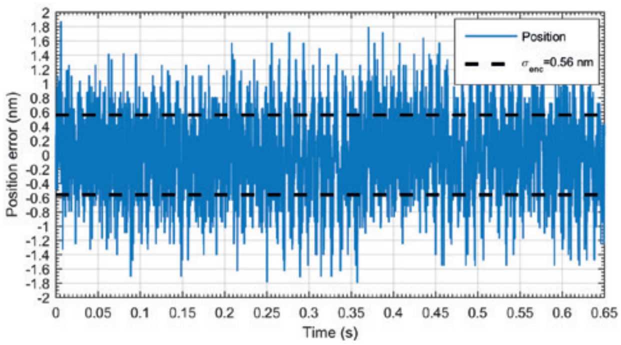
SEM image of the chipped diamond tool after diamond turned sample coatings with claimed high phosphorous content.

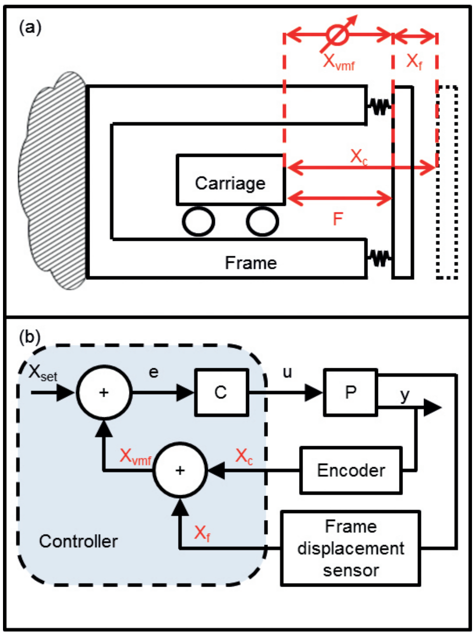
Mechatronic and Control Development of a Virtual Metrology Frame Technique for Ultra-Precision Machine Tools

Jonathan Abir









In recent decades numerous research efforts to develop ultra-precision small size machine tools have been undertaken, which requires high machine accuracy, high stiffness and dynamic properties. The existing solutions for these requirements are often antagonistic to the small size constraint.

The effort to reduce the size of the machine lead to low stiffness design, which is the bottleneck achieving ultra-precision manufacturing due to machining errors. These errors can be reduced by increasing feedback gains and servo bandwidth; however, the amounts by which these parameters can be increased are limited.

A novel concept, a virtual metrology frame, was developed to enhance the dynamic performance of a machine with a low stiffness frame. Machine performance is directly affected by the stiffness of the frame and reference system; the realisation of an unstressed (virtual) metrology frame can enable superior dynamic performance. The developed concept does not require physical components associated with the metrology frame; this is ideal for machine tools with requirements for small footprint and ultra-precision performance. The concept was demonstrated on a linear motion system, a simplified version of a compact size CNC machine; the servo bandwidth, tracking error, and dynamic stiffness were improved by 36%, 70%, and 41% respectively.

Realising the concept required the development of a technique for measuring frame dynamic displacement, an accelerometer based dynamic displacement technique was developed; it offers real-time, low noise, and a low delay feedback signal, with a displacement error of < 30 nm.

The machine frame dynamic properties and its sensitivity due to temperature changes in the operating environment were simulated and experimentally measured; this led to design improvements. The new dynamic properties were simulated and analysed showing improvement of up to 65% of resonance frequencies.

This work ties theoretical analysis with experimental testing to derive new mechatronic techniques and improve the mechanical design of a linear motion system to advance the machine to be more precise and therefore more productive.

Control of Residual Stress and Failure Mechanisms for Laser- Assisted Cold Spray High Performance Coatings

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

Many techniques such as peening and heat treatments are used to post process metallic coatings. Such treatments provide a number of advantages such as protection against corrosion or abrasion, increasing the lifetime of a component.

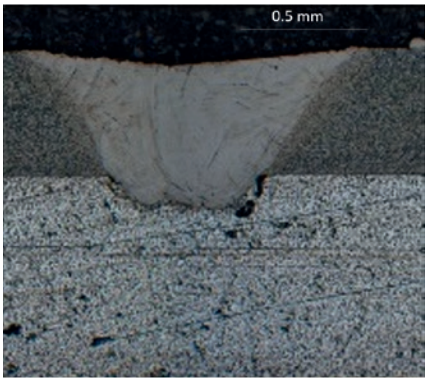
The interaction of a laser beam with a material is capable of permanently modifying the materials properties, such as its crystalline structure, morphology or stress state. Using a laser it is possible to transfer a large amount of controlled energy into a material in a precise region at the surface, over a short time scale.

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 investigating the failure mechanisms of a high performance coating deposited by laser-assisted cold spray. For this project a tungsten carbide coating is being used. This coating can be used to increase the wear resistance of a protected surface. High performance coatings such as this are beneficial for industry as they can greatly increase the lifetime of components leading to significant cost savings.

Acoustic emission techniques combined with mechanical testing have been used to evaluate and characterise coating failure in the deposited tungsten carbide coatings. Further work is being done to understand the thermal stresses generated during deposition, as these can lead to significant residual stress in the final coating. By minimising these stresses it will be possible to make more durable, crack free and longer lasting coatings.



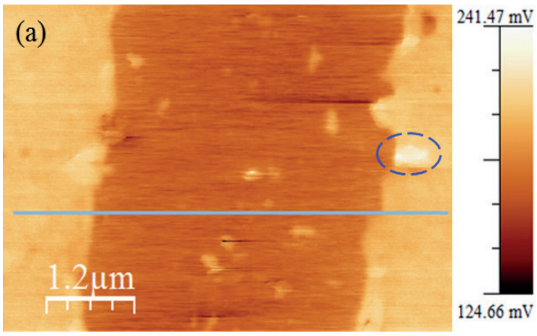
Cross section of three lines of adjacent layer pulses used to bond Ti 6-4 (top) onto an aluminium substrate (0.8 mm spot, 6 ms, 1400 W).

Femtosecond Laser Processing of Graphene for Device Applications

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

Lithography is the typical method to fabricate a graphene device. 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 a graphene device in a maskless way, for its capability to provide free-form post-patterning, limited thermal effects and high processing speed.

We have evaluated the femtosecond laser ablation process of graphene on $Si0_2$/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 that 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 analysed by Raman. This could provide a new way to functionalise graphene for biosensor applications.



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 bilayer graphene is indicated by the dashed circle, having a higher CPD than the monolayer graphene.

Precision Glass Microstructuring Using Femtosecond Laser Induced Chemical Etching

Wenhe Feng | Sponsor: Amplitude Systèmes

Femtosecond laser induced chemical etching (FLICE) is a micro-fabrication technique that allows versatile production of 3D structures in glass. In this study, an alternative FLICE technique that employed potassium hydroxide (KOH) was developed. A processing recipe for fused silica glass was established, and key processing parameters were found to fulfil criteria such as high etch rate (5 μm/min) or the selectivity (up to 9000:1). A surface fabrication route was developed to allow dimples, deep channels or holes to be machined. A 3D design rule was established via the fabrication of thick tunnels and chambers to achieve a high pattern resolution with a low collateral damage. Finally a CAD/CAM approach was set up to manufacture arbitrary 3D geometries. The mechanism that enhanced etching was also found dependent not only on the Si-rich network but was also heat induced by the laser overdose. A prototype optofluidic chip for Raman detection of bacteria in water was designed and fabricated with FLICE. The study suggested an applicability of an effective and HF-free FLICE process fulfilling the need for etch rate or etch selectivity for the fabrication of a functional optofluidic chip.

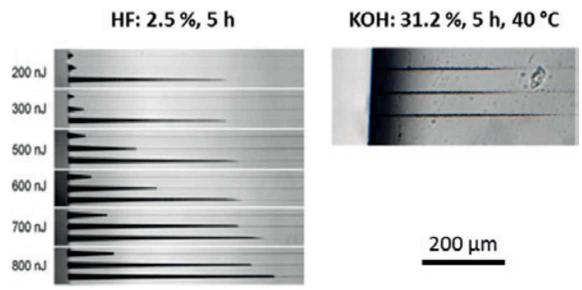


Figure 1. A comparison between KOH and HF etched (Hnatovsky et al, 2005) fused silica pieces.

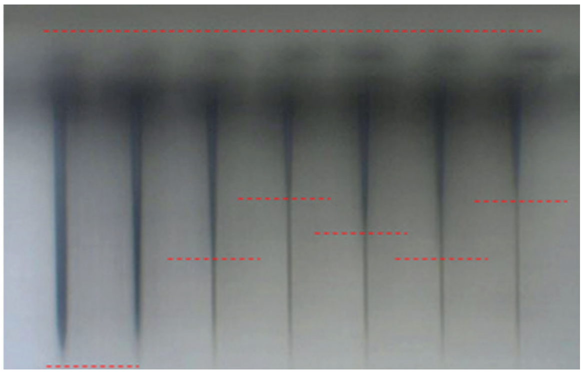


Figure 2. The surface channels fabricated using FLICE.

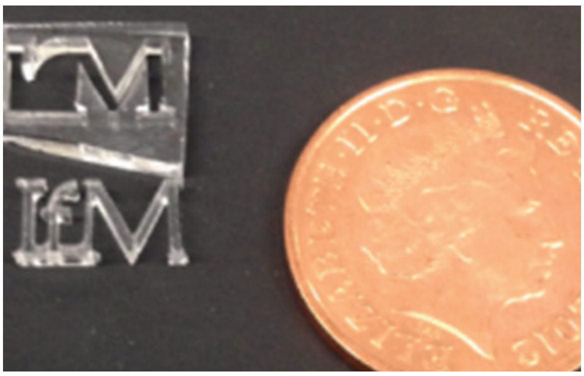


Figure 3. An IfM logo fabricated using FLICE, seated against a 1p coin.

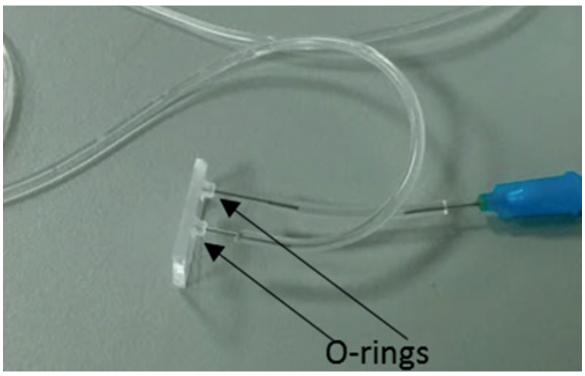


Figure 4. A bespoke chip with push-fit microfluidic tubings connected to the receptors.

The Use of Femtosecond Laser Processing for the Removal of Gallium from FIB Milled Silicon

Matt Bannister

Frequently, FIB systems employ a gallium liquid metal ion source for several reasons; gallium may be kept liquid with minimal heating required, and offers excellent milling properties on a wide range of substrates. However, the FIB milling procedure results in significant lattice damage and implantation of the gallium ions within the substrate surface, changing many properties of the material and preventing FIB processing from being implemented in a wider range of applications.

Therefore there is a need to be able to remove gallium and reverse the damage caused during FIB milling. Ultrafast laser processing was investigated as a possible option for this by using laser pulses of the order of several hundred femtoseconds and below. The interaction occurs on a non-thermal timescale, which may offer an optical solution without causing damage to any thermally sensitive components of a device.

Investigations were carried out using a Satsuma ytterbium fibre laser, operating at a pulse duration of 280 fs. Silicon substrates were milled using a gallium FIB at ion doses of the order of 10^{18} 10^{20} ions/cm^2 and subsequently processed using the ultrafast laser.

It was shown that FIB milling resulted in a decrease in laser induced damage threshold approximately 50% from the un-milled substrate. It is suggested that this is primarily due to the approximately 30 nm thick amorphous layer that is created at the surface of the silicon during 30 keV gallium bombardment.

When processing below the experimentally determined damage threshold, no significantly measurable change in gallium concentration was observed. The concentration was measured both directly by Rutherford Backscattering Spectroscopy (RBS) and indirectly using Kelvin Probe Force Microscopy (KPFM). Two sample spectra obtained from RBS analysis, carried out at the University of Surrey, are shown in Figure 1; from the overlapping shapes it can be concluded that gallium has not diffused either into or out of the surface in any significant manner during laser processing. KPFM analysis shows no statistically significant difference in surface potential between laser processed, FIB milled and non-laser processed, FIB milled regions of silicon.

Further evidence supporting these findings also includes Transmission Electron Microscopy (TEM) analysis and Micro-indentation analysis of the laser processed, FIB milled regions. TEM images showed no significant change in thickness of the amorphous layer, indicating no lattice damage reversal had occurred due to laser processing. Additionally, micro-indentation analysis showed that the surface softening caused by the FIB milling process had not been reversed by sub-threshold laser processing; an example load-displacement graph is shown in Figure 2.

Therefore all experimental evidence shows that removal of gallium and FIB induced damage from FIB milled silicon is not possible using ultrafast laser processing below the damage threshold. It is suggested that this is due to the timescale of the laser pulses, as dopant out-diffusion is well known using conventional thermal annealing.

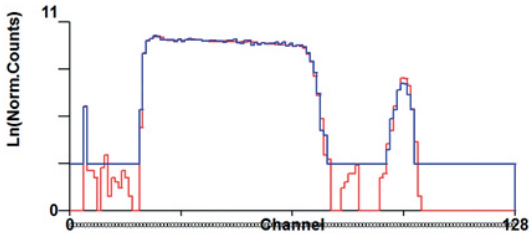


Figure 1. RBS spectra of FIB milled silicon (blue) before laser processing (red) after laser processing

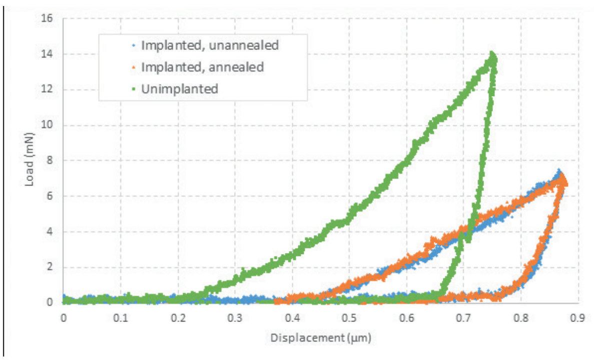


Figure 2. Sample load-displacement curve obtained by microindentation showing no reversal in surface softening following laser annealing

The Improvement of the Resolution and Frame Rate of Optically Addressed Spatial Light Modulators (OASLMs)

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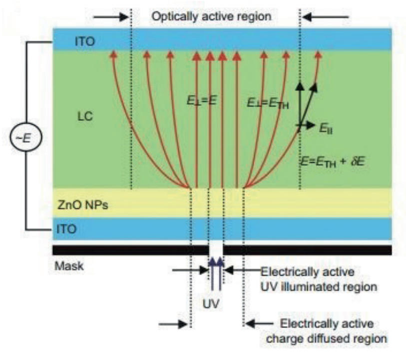
The research direction of this project is to improve the resolution and frame rate of the optically addressed spatial light modulators (OASLMs). OASLMs are attracting more and more attention due to their potential advantage of better resolution and larger panel size. These advantages are crucially important because better resolution provides smaller pixel pitch and thus larger viewing angle. On the other side, larger panel size means larger sized hologram, containing more information and generating larger image size.

Currently the OASLMs are still limited in resolution due to the electrical fringing field and lateral diffusion of the charge carriers. The limitation in frame rate is caused by the fall time of the photoactive layer, in which case, the discharging of the charge carriers is slow when the write light is off.

A few techniques have been developed to improve the resolution and the frame rate. The goal is to fully understand the operation and physical process of OASLMs through simulations and implement the improvements through experiments.



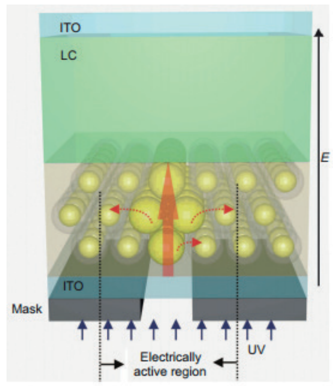


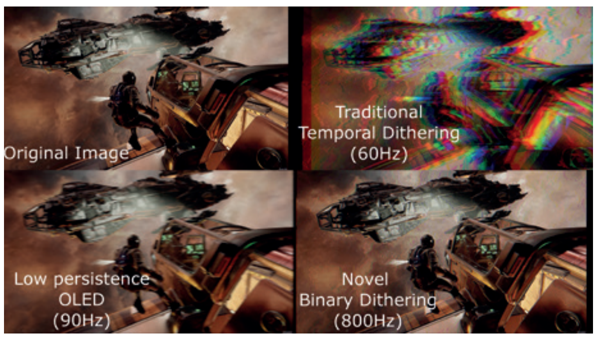
Image source: Shrestha, P. K., Chun, Y. T. and Chu, D. (2015). A high-resolution optically addressed spatial light modulator based on ZnO nanoparticles, Light: Science& Applications, 4(e259), 1-7.

Binary Dithering Schemes and Display Motion Performance

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

This project is an investigation into perceptual errors when viewing video images in a high-speed environment – with relative motion between the display and retina, as when tracking a moving object on a display, or where the viewer is interacting with displayed content, as with real-time rendered virtual environments. Virtual Reality is an example of a use case where both image sharpness and latency are critical, but where current display technology falls short, with noticeable visual errors. Part of the project consisted of defining metrics to quantify the various motion errors, in a way that allows comparison between very different technologies. The theoretical minimum error metrics for Binary Displays, such as DMD projectors, operating in existing and novel modes were calculated, with the result that some schemes are superior to existing technologies such as LCD and OLED. The image below shows a simulation of the distortions caused by motion. The novel binary dithering scheme has lower blur and displacement, and offers a higher refresh rate.

As binary dithering displays are so promising, the current focus is on implementing and testing novel display schemes. The image below is a recent result showing the accurate display of colour using a novel technique that allows much greater speeds and image sharpness than conventional methods.



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, if capable of being progressed to a freeform manufacturing method, will offer it a unique placement within the additive manufacturing landscape. The practicality of this development is being investigated and the best concepts progressed, in four supporting work streams.

Competition and Opportunity Investigation

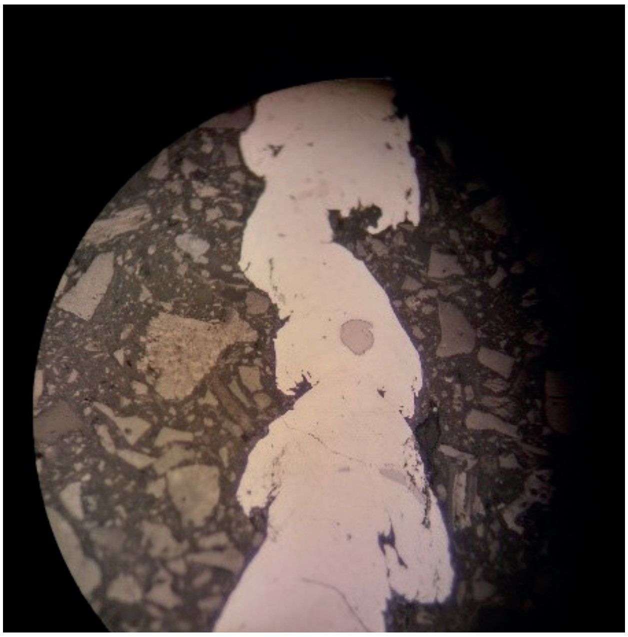
Competitive techniques in both traditional and additive manufacturing sectors have been studied to analyse the relative strengths and weaknesses of each system when considering a cold spray additive manufacturing system specifically the unique benefits offered due to the low processing temperatures. Opportunities for this potential system have 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.

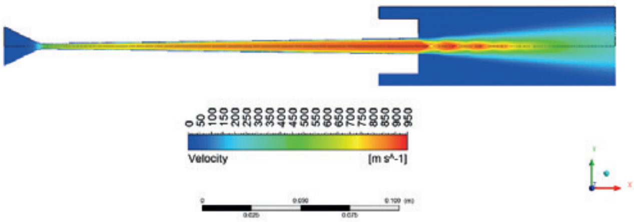
Concept Generation and Experimentation

The primary 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 considered include hard or sacrificial backstops to spray against, profile shaping using 2D masks or stencils, and flow separation techniques. Initial tests have been conducted with hard backstops to allow bulk deposition, with following trials to investigate the effects of continuous flow on the backstop and optimisation of the deposited single-track wall height. Trials of low height masks are also being conducted for the production of high fidelity tracks.

CFD Simulation

The process has been modelled, using the ANSYS Fluent CFD package to determine the flow structure and shockwave formation 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. This will prove important when





introducing objects into the flow path at the nozzle exhaust, as these will affect the generated shockwave and thus the powder deflection and velocity during deposition.

Visualisation

Schlieren photography is being implemented for the gas jet only, to prove the effects of introducing obstacles to the gas jet, and validate the CFD model created. Particle image velocimetry is also being considered for the measurement of powder speeds in the exhaust, but would not provide data on the flow patterns or speed of the gas.

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

Yoanna Shams | Email: ys420@cam.ac.uk | Sponsor: M-Solv Ltd and the Centre for Science Technology and Innovation Policy

Current diagnostic capabilities such as microscopy, culture, immunoassays and nucleic acid amplification are mainly lab based analytical techniques and are expensive, time consuming and only performed by trained personnel [1]. Therefore we need to develop technologies to complement lithography that can enable the precise patterning of advanced functional materials that are often sensitive to lithographic processes.

This research focuses on defining a novel and versatile hybrid technology combining digital liquid deposition techniques and laser ablation to deliver advanced sensing devices. This hybrid technique will be able to provide low volume niche manufacturing on a broad range of surfaces where current lithography techniques are not feasible.

Inks using functional and biological materials are formulated and then processed using inkjet printing and ultrafast laser ablation.

Inkjet Printing

- Drop-on-demand
- Digitally controlled and used commercially for short print runs and late-stage customisation, with typical printheads containing 100 – 1000 nozzles.
- Traditionally used for graphical printing but has been demonstrated with biological and functional materials.
- Resolution within 10s of micrometres.

Some of the initial work on inkjet printing functional materials has been focused on the delivery of iron oxide catalyst on silicon substrates for the growth of structured carbon nanotube forests.

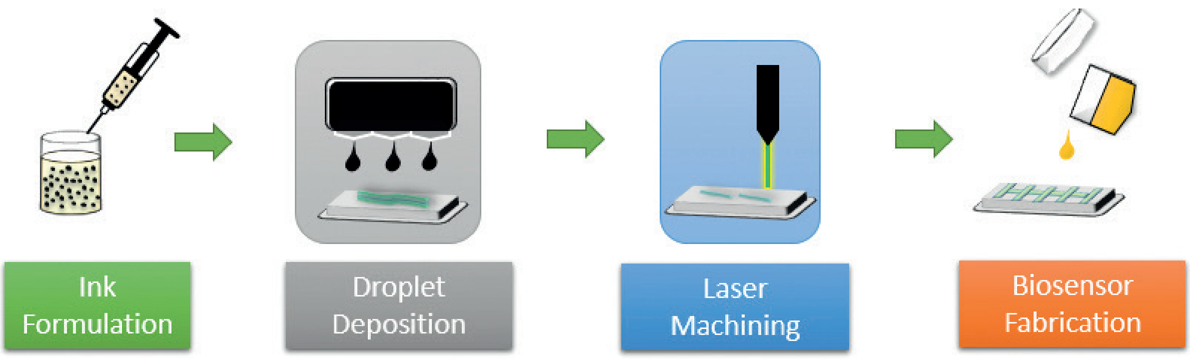
Ultrafast Laser Ablation

- Digital control for ultra - precision patterning sub-micron resolution features
- Suitable for shaping biological and functional materials due to no thermal energy build up in the surface causing heat affected zones.

Some of the initial ultrafast laser patterning work has been focused on printed and PVD coated iron oxide catalyst on silicon wafers and looking at the effects of the laser on the nanocatalyst islands critical for the growth of carbon nanotube forests. Early experiments on some mCherry fluorescent protein have also been carried out.

Biosensing Applications

- Controlled growth and patterning allow different biosensor structures
- CNTs can be functionalised for biosensing applications achieving high sensitivity and high speed detection
- Different proteins and biological materials can be patterned to achieve multidiagnostic capabilities



Hybrid technology combining droplet deposition and ultrafast laser ablation for biosensing applications

[1] Tothill, I. E. (2001) "Biosensors developments and potential applications in the agricultural diagnosis sector," *Comput. Electron. Agric.*, 30(1), 205–218.

Real-Time Metrology of Micro-Targets for High Power Laser Systems Operating at High Repetition Rates

Shah Karim | Email: ezxsk3@nottingham.ac.uk | Sponsor: Science and Technology Facilities Council

Project Overview

Microtargets irradiated by high power lasers (HPL) enable experimental study of a wide range of objects and materials under extreme conditions, for example, ion production for potential future oncology techniques, laboratory astrophysics and 'inertial fusion energy' (Figure 1).

The target fabrication group within the Central Laser Facility (CLF) of the STFC Rutherford Appleton Laboratory (RAL) supplies a wide range of microtargets (Figure 2), for example, micro-assembly, thin film coating, low density materials, to the laser user communities at home and in the international arena. As such, a shift of recent lasers development towards high repetition rate HPL has direct implications in the capacities and capabilities of the fabrication group. This is because established methods of target fabrication are less suited to meet the high volume target demands for HPL. This has created a need for a source of targets that is reproducible and also flexible around a common target placement mechanism, representing a robust solution for 'targetry stream' for the high repetition rate (HRR) laser systems. To fully realise the potential of future HRR laser systems, real-time metrology will be required at matching rates. Hence, this PhD project aims to establish the metrological requirements of microtarget fabrication and microtarget delivery system which will be necessary for the development of matching laser capability of the CLF to operate it as a HRR laser facility.

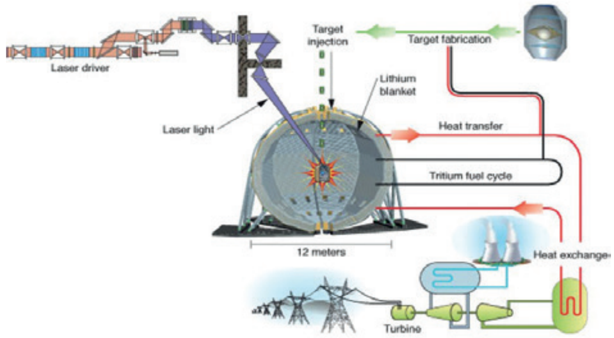


Figure 1. Application of high-repetition high power laser system (conceptual view of a typical power plant with separated target factory, laser driver, fusion chamber and turbine generator). Source: https://str.llnl.gov/

Current Research

An in-depth literature review has been carried out to understand the requirements of targetry stream (mass production of target and delivery of targets to the chamber in high numbers) for the CLF's Astra-Gemini laser system. Current research focuses on developing a kinematic model for Astra-Gemini's new target positioning system (Figure 3), known as high accuracy microtargetry system (HAMS) to establish a framework that will facilitate a systematic approach to the analysis of errors and also to the assessment of their influence on the accuracy of the positioning and orientation of microtarget.

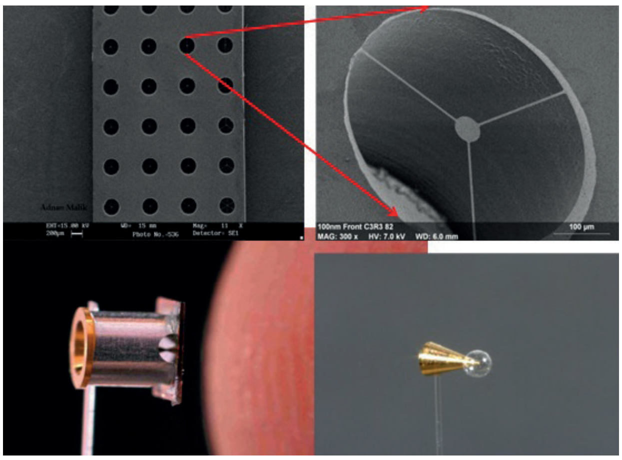


Figure 2. 2D and 3D shape microtargets. Source: CLF, STFC.

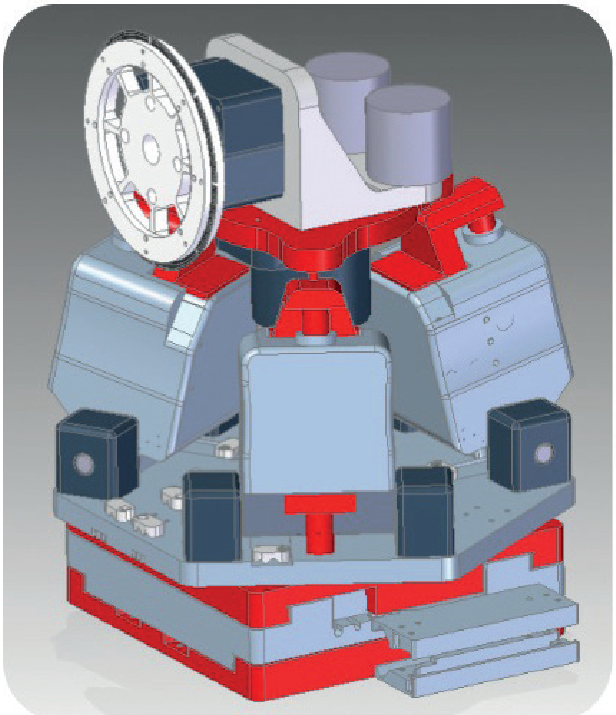


Figure 3. CAD model of HAMS. Source: Proc. SPIE 9211, Target Diagnostics Physics and Engineering for Inertial Confinement Fusion III, 921107 (2014).

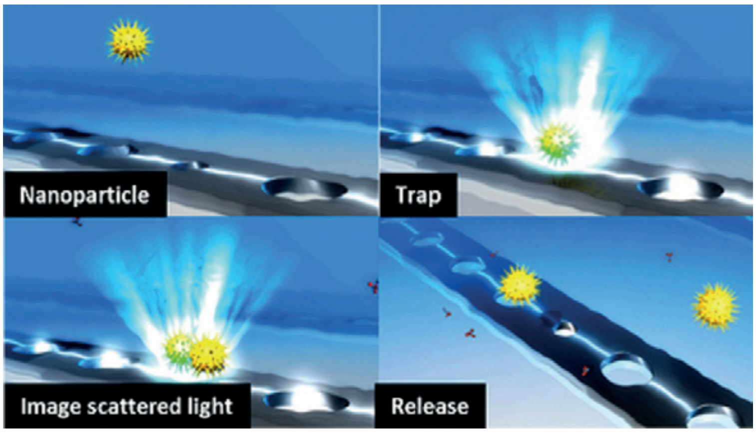
The Development and Optimisation of an Optofluidic Nano Tweezer System for Trapping Nanometre Crystal in X-Ray Diffraction Experiments

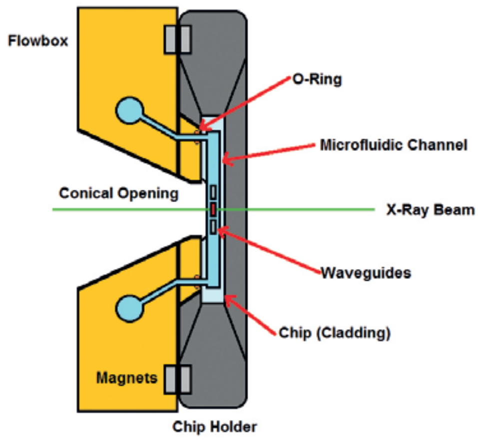
Alexandre Diaz | Email: ajd216@cam.ac.uk | Sponsor: Diamond Light Source Ltd and Innovation Policy

X-Ray crystallography has become the technique of choice for the analysis of complex crystalline structures like proteins. Despite significant advances in x-ray beam generation, quality, detection hardware and post-detection modelling technology, the currently implemented electromechanical sample loading processes still falls behind in comparison. This substantially reduces the quality of the measured Bragg diffractions and limits the size of the crystal samples to the micron domain. This is due to the inherent limitations of electromechanical systems (such as robotics), given movement backlash impairing the positioning, and the requirement of cryogenic cooling which alters the structure of the crystalline sample.

Currently proposed alternatives have had varying degrees of success, but have yet to unlock the coveted submicron sample loading domain. This project proposes a novel sample loading methodology, which combines elements from microfluidics and optical tweezing technology. The proposed device is an "off the shelf" optofluidic chip which has been modified for the scope of this project and nano-tweezer system, which traps samples via evanescent fields emitted from silicon nitride waveguides transmitting a 1064 nm biologically friendly laser beam. The project also aims to develop a robust testing methodology for the optofluidic chip performance and characterisation, to derive the optimal trapping parameters of a range of protein crystals of both micron/submicron dimensions and of diverse geometries.

This will be achieved by experimental measurement of the trapping frequency, particle procession distance and velocity across the waveguide, through the control (and potential automation) of the particle concentration, laser power and microfluidic flow rate variables. Using optimum parameters, live beamline x-ray beam diffraction experiments will be undertaken at the **Diamond Light Source** I24 MX beamline to detect the Bragg diffractions of optically trapped protein crystal sample.





Roll-to-Roll Fabrication and Design Optimisation for Flexible Smectic A Liquid Crystal Displays

Chris Williamson

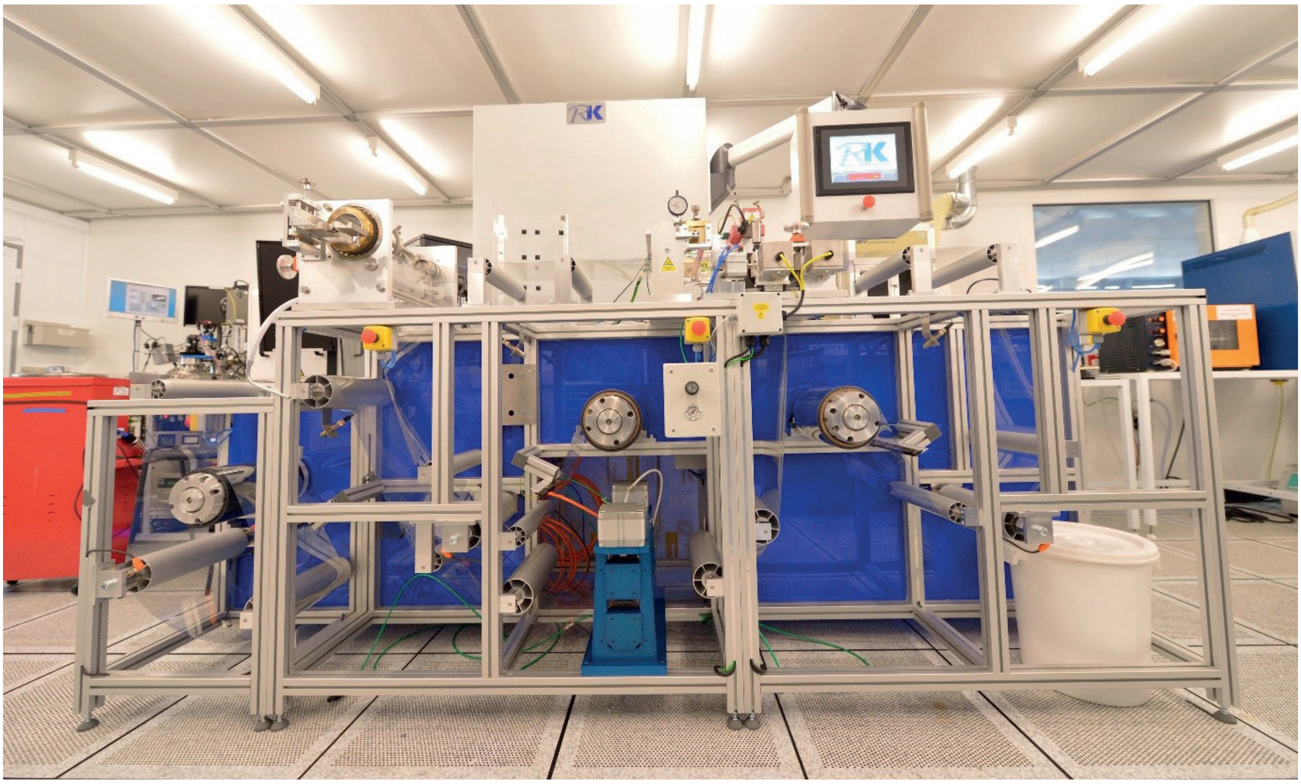
The aim of this PhD research was to develop an efficient manufacturing system for Smectic A liquid crystal displays to facilitate commercialisation of the technology. Dual sided lamination of a flexible organosiloxane based liquid crystal cell has been realised on a continuous roll-to-roll (R2R) process which enables automated continuous production of flexible PET plastic display panels. Processes include tension control, screen printing and moisture control, heated die coating and die cutting 15cm^2 panels.

The main advantages of our technology includes being stable in multiple states whereby upon application of an electric field, the Smectic A (SmA) liquid crystal arranges its molecular structure to allow scattering of light. When the electric field is removed, the liquid crystal state is retained. Drivers were created to provide a series of 50 Hz pulses to induce a scattered texture and a 2 KHz series of pulses for a clear texture. The extent of scattering is determined by the length of the pulse chain. In the clear state the cell is transparent which allows for uses including smart windows.

The research has led to Flexypix being incorporated in July 2016. The technology is an energy efficient solution for improving the living environment in a building by modulating light and heat entering through windows. In turn it can improve productivity in an office and lower energy bills by allowing air conditioning use to be reduced. The technology is also an excellent advertising tool as it is an eye-catching interface capable of displaying information which could improve sales for a company. Our technology has been reported by the **University of Cambridge**, **ITV** and **Cambridge News**.

Through analysis of scattering textures, it has been observed that SmA cells initiate scattering from a defect site before it propagates from this point. Physical surface defects can induce a localised electric field which is how the scattering texture is initiated. The optimal structure for generating strong electric fields has a high aspect ratio. This structure has been realised with vertically aligned and patterned arrays of carbon nanotubes (CNTs) which have been grown and electrically characterised using field electron emission. The research resulted in a new technique to reduce the threshold voltage to 15V which is a 40x improvement over typical field emission from a CNT. We are in the process of filing a patent for this research.

Completed R2R system



Transparent textures

Opaque textures

Ultra Precision Hybrid Laser-FIB Platform

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

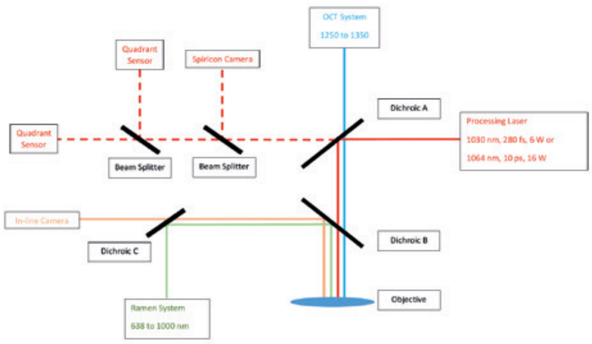
The demand for ultra precision devices is continuously increasing due to ever expanding applications in electronics, bio-medical, optical and energy devices. This is causing demand for a processing method which is capable of prototyping and creating small batch quantities of these devices with a short lead time and low cost.

The integration of ultrafast lasers machining and focused ion beam (FIB) milling has been proposed as a solution. There are several possible advantages of combining these two platforms:

- A higher degree of flexibility compared to more established technologies.
- Reduced production time for device prototyping, continuous customisation or low volume devices.
- Capable of a large range in feature sizes from nm to mm.
- Reduction of ion milling reduces material degradation due to ion implantation.

A wide range of metrology techniques have been identified and evaluated with regards to use as a feedback option for ultrafast machining. Beam stability tests have taken place to determine the initial open-loop performance of the system and the level of closed-loop control that needs to be implemented to improve beam stability.

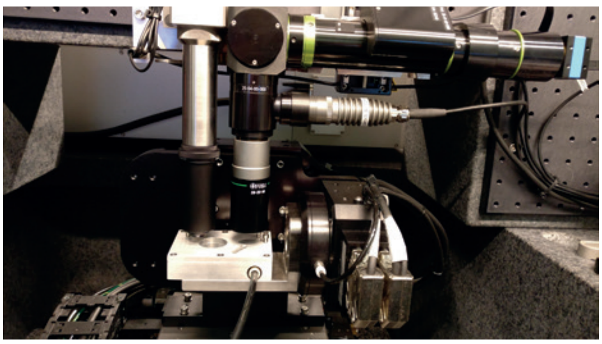
A further technology which is being integrated is a Raman system which will allow the in-situ characterisation of carbon allotropes. For example, when used to characterise graphene the Raman system determines presence,

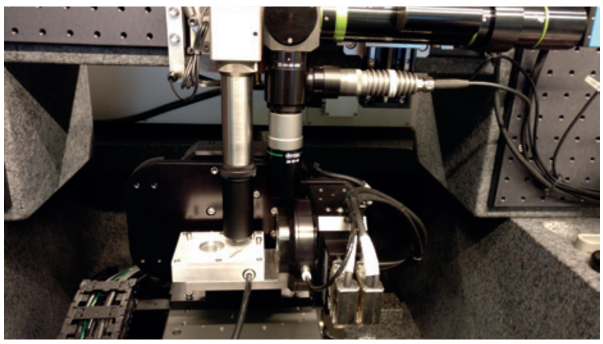


numbers of layers, and defects within the body of material. When combined with the machining capabilities of ultrafast lasers the characteristics can be modified. This allows for characterisation, modification and evaluation to occur on a single platform which provides a singular process for device manufacture.

This had lead into the development of a custom optical train design to allow the integration of the various technologies as shown above.

With completion of the construction of the ultrafast platform in the last month the next stage of development is to begin investigation into closed-loop graphene machining and the use of oblique angle and OCT for accurate geometrical machining. Tests have begun characterising the platform accuracy, ablation focal point and microscope position.





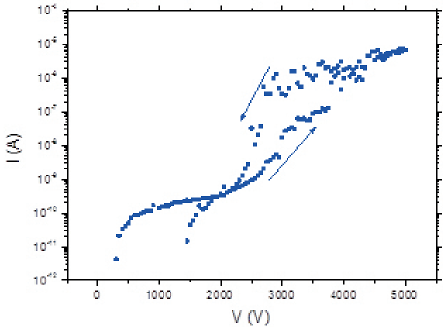
Ordered Nanomaterials for Field Emission

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

Field emission has long been studied for the potential in applications such as microwave amplifiers, travelling wave tubes, electron microscopy, and x-ray sources. This project focuses primarily on x-ray applications, with the intention of integrating an optimised chip design into a portable x-ray gun towards the end of the project.

A large meta-analysis of the materials used in field emission applications was made. Materials are required to show high maximum current density as well as low turn on electric field to be considered as a promising material in field emission. 1D and 2D materials were shown to have an average turn on field half the size of 3D/bulk materials. The best performing group of materials were the nanocarbons including carbon nanotubes, graphene, carbon nanowalls and carbon nanofibers.

A number of different carbon nanotube configurations have been synthesised. The morphology of the emitter plays a large role in emission characteristics. To determine the full extent of morphology influence, field emission from a parallel plate set up is measured. A number of studies are being performed to determine the underlying physics of the emission mechanism. These include studies in pressure, optical excitation, in situ residual gas analysis and stability.



A typical field emission curve and hysteresis observed. Arrows indicate direction of up (increasing voltage) and down (decreasing voltage) sweeps.

Hysteresis is commonly seen amongst carbon nanotube and carbon based field emitters when exposed to a voltage loop. The aim of the above studies is to understand the physics of emission and the source of hysteresis. Using data collected from the above studies, we can also examine the nature of the hysteresis and determine a theory about what causes it and how to reduce it for applications.

Production of High Current Field Emission Carbon Nanotube Based Cathodes

Francisco Orozco | Sponsor: Air Force Office of Scientific Research

Project overview

Advanced cathode materials are needed to produce stable, high current electron beams needed for compact, high power, high frequency, vacuum electronic devices. Current state of the art thermionic cathodes requires high operating temperatures, resulting in inefficient power consumption, poor reliability, and shorter lifetime.

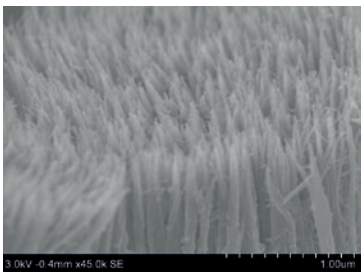
High powers associated with thermionic cathodes require the incorporation of device cooling, which in turn leads to additional complexity and added weight, both of which are undesirable. Field emission (FE) cathodes are an appealing alternative to thermionic cathodes due to significant reduction in power requirements for such operating devices. Power reduction in the FE devices also offers an opportunity to reduce the size of the cathode device significantly.

Materials used in this project are carbon nanotube (CNT) fibres and films. CNT's are being used as base material due to high aspect ratio, chemically inert, high thermal conductivity, small tip radius and high mechanical strength makes them an ideal material for field emission (FE).

Conclusions from this project

This project has bridged the gap in making repeatable field emission devices using innovative production techniques with state of the art materials.

- Process developed for production of repeatable CNT based field emission devices.
- Increased field emission of Cambridge material by 450% by coating the CNT material using an innovative process.
- Increased contact and reduction of resistance by 50%.
- Removal of impurities enhancing field emission.
- Array scale up from 2 fibres to 169 in a single repeatable array with increased contact.


Edge of a laser cut CNT fibre showing the bundles of individual CNTs.

Holographic Enhancement of Fibre Optic Sensors

Jaliya Senanayake | Sponsor: Michell Instruments

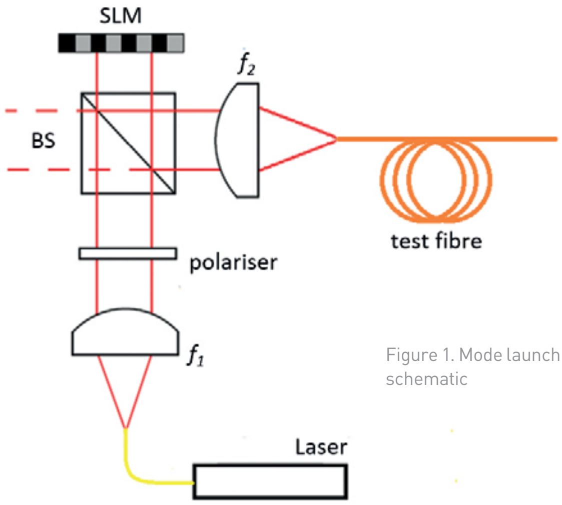


Figure 1. Mode launch schematic

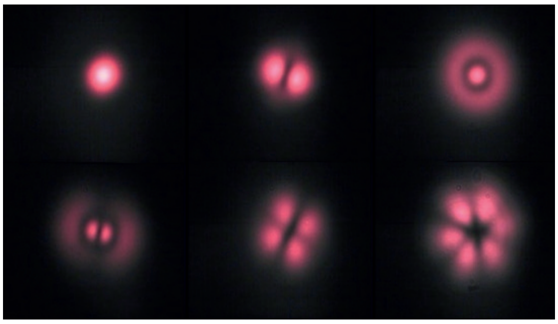


Figure 2. Spatial distribution of light at the fibre output confirming selective mode launch

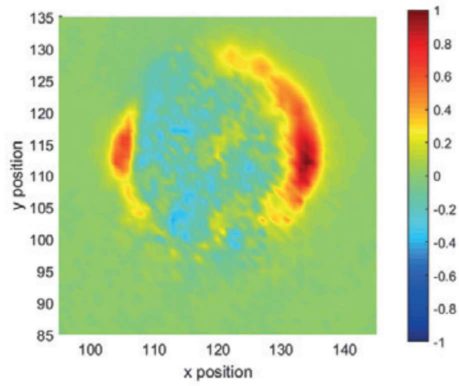


Figure 3. Colour-map representing the interaction of the evanescent field with external media when an offset spot is launched into each coordinate across the fibre surface

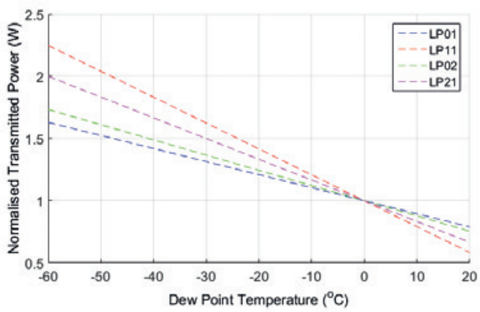


Figure 4. Modal sensitivities of side polished fibre performing dew point temperature sensing

Since their first practical applications in the mid-1960s, fibre optic sensing has grown into a large scale industry, driven by a unique set of advantages they offer over conventional electronic sensor technologies. This research investigates if the performance of a fibre optic sensor is reliant on the modal decomposition of light within the fibre, and if this may be exploited to improve the performance of sensor devices.

A holographic launch scheme is developed to control the modal excitation of optical fibres. For a given fibre, solving the scalar wave equation in its discrete form, the bound modes are determined with high accuracy (percentage errors ~0.0012%). Computer generated holography is then used to determine holograms whose replay fields yield a high overlap integral with these fibre mode profiles. Focusing these replay fields onto the fibre facet, selective mode excitation is achieved (the mode launch schematic used is shown in Figure 1). The high accuracy required of the replay field for selective mode launch is achieved by exploiting the adaptive nature of the SLM, with optimisation algorithms both self-adjusting for misalignments using blazed gratings and self-correcting for aberrations using compensating phase patterns (formed of up to 35 weighted Zernike polynomial terms). Viewing the spatial distribution of light at the fibre output (over short lengths of fibre where mode mixing is limited), the injected modes are clearly visible, confirming the efficacy of the launch scheme (see Figure 2).

Using an offset spot launch to excite differing combinations of modes, it is demonstrated that the exposed evanescent field of a side polished fibre is dependent on the modal decomposition of light within the fibre. This is illustrated in Figure 3, where the colour-map represents the extent of interaction of the evanescent field with an external media when the offset spot is launched into differing coordinates across the fibre facet. Further comparing the normalised responses of a fibre performing dew point temperature sensing, with distinct modes injected, the sensitivity corresponding to each fibre mode is shown to differ (see Figure 4). This confirms that selectively exciting the most sensitive mode can improve the device sensitivity (in the given example by 38% compared to an overfill launch where all modes are excited equally). Further in this research, the growth of thin poly(HEMA) coatings on the surface of side polished fibres by polymerisation via the fibre evanescent field is demonstrated, and the swelling behaviour of the polymer exploited for sensing ethanol concentration, pH and humidity.

Development of a Precision Fibre Optic CO_2 Sensor – The Potential Use in Healthcare Assessment

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

The ever increasing desire for portable point-of-care devices has led to the requirement that sensing elements must be able to deliver high accuracy, sensitivity and specificity, yet possess micro-scale dimensions. Optical fibres have the potential to provide a sensing platform with the necessary characteristics, as they have compact dimensions, can be modified to provide sensitivity to a range of analytes, and offer a means for multiplexing a number of sensors within a single optical fibre. Numerous sensor designs are available that exploit optical fibre devices coated with functional materials to accomplish the detection of an analyte. In this project, the sensing platform is the long period grating (LPG), and an in-fibre grating device that couples light from the core of the fibre into the cladding, resulting in distinct attenuation bands in the transmission spectrum of the fibre. These resonance bands display inherent sensitivity to variations in refractive index of the material directly surrounding the optical fibre. The interest here is in coating the LPG with a material that shows an affinity for CO_2, and in enhancing the sensitivity of the device by optimising the properties of the LPG and the thickness of the coating.

The project initially investigated the fabrication of novel LPGs structures with features that can be used to distinguish between different physical parameters acting on the fibre (refractive index, temperature), extending previous work by also improving their sensitivity to measurands. This approach will be integrated into the final design of the sensor to allow discrimination between temperature fluctuations and changes in CO_2 concentration.

An extensive review of potential functional materials led to a decision to investigate the use of ionic liquids as the functional coating. Many ionic liquids exhibit a high affinity for CO_2 while also possessing inherit hydrophobic tendencies making them an ideal coating material for the sensor. These materials have not been used in combination with optical fibre sensing platforms before. Investigations of methods to stabilise the material such that it can form a robust coating, and the means for coating the material onto an optical fibre, have dominated this year of study.

A successfully coated LPG can be seen in Figure 1. Initial work on characterising the CO_2 sensitivity of the coated LPG is currently underway. The results from these experiments will inform the direction of future work regarding coating characteristics (thickness, homogeneity of deposition) and refinements required to optimise the precision of the fibre optic CO_2 sensor.

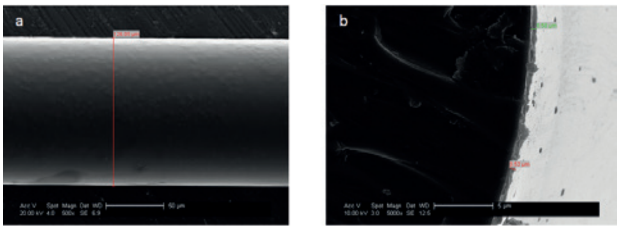


Figure 1. SEM images of coated optical fibre from the side (a) and fibre tip end (b).

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

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. A deposition platform has been assembled consisting of a tungsten hexacarbonyl precursor delivery system, a vacuum chamber with a laser window. Depending on the desired substrate material and track width, two lasers are available for use: a 1064 nm continuous wave (CW) laser with a 40 µm spot at a maximum power of 20 W; or a 405 nm wavelength,

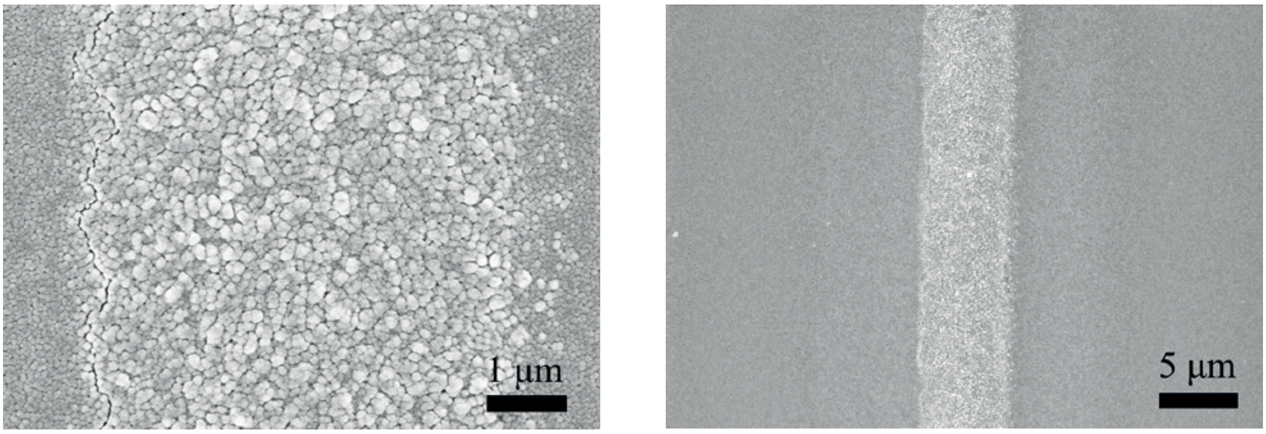


Figure 1. SEM image of a LCVD written track of tungsten using a 405 nm CW laser at a speed of 10 µm/s on SiO_2 coated Si substrate.

CW, 10 µm spot at 0.5 W maximum power. Using this system, tungsten has been deposited in a 2D free form pattern, defined by the laser on silicon, silicon dioxide (Figure 1), copper and stainless steel. The microstructure and elemental composition of the deposits are comparable to that of large-area chemical vapour deposition methods using the same chemical precursor. The contact resistance and track resistance of the deposits has been measured using the transfer length method to be at least 17 times the resistivity of bulk tungsten. The deposition temperature has been estimated from a laser heat transfer model accounting for temperature dependent optical and physical properties of the substrate. The peak temperatures achieved on silicon and other substrates are higher than the thermal dissociation temperature of numerous precursors, indicating that this technique can also be used to deposit other materials such as gold and platinum on various substrates.

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

Jiho Han

Introduction

Traditionally a laser beam shaping problem is defined as redistribution of the intensity profile into another more desirable profile. Attempt goes as far back as when Frieden (1965) discussed a method for obtaining a top hat beam profile. Top hat beam profiles are still very useful today for applications such as laser machining, laser surface hardening, tattoo removal, keratectomy, and tissue welding. Today, beam shaping methods are much generalised, and with the aid of phase holography, we are now able to transform a laser beam into more or less any other beam arbitrary beam shape we desire. In addition devices such as Spatial Light Modulators (SLMs) or deformable mirror arrays grant us a programmable beam shaping element, allowing us to change the beam shape at more than 50Hz.

However, SLMs have a fairly modest power handling capabilities at around 15 W/cm^2 (Norton et al. 2010). Deformable mirrors can have up to 400 W/cm^2 of power handling capacities, but the degrees of freedom available for modulation are severely limited at around 10-100. Therefore, it would seem that currently, high fidelity dynamic beam shaping and high power handling capabilities are incompatible.

Though in this work, we focus on beam shaping, the incompatibility between throughput and resolution is evident in other contexts: scanning a focussed laser beam offers high resolution while defocussed beam offers high through put, but the two are incompatible!

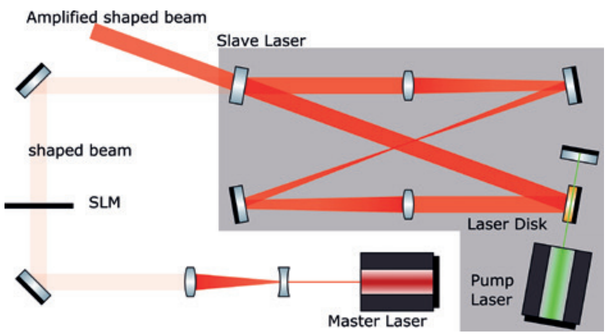
Motivations

If the dynamic beam shaping capabilities of Spatial Light Modulators (SLMs) could be made compatible with today's high power lasers, we may be able to process a 2D area through single exposure to a shaped high power laser beam, instead of relying on laser scanning. Process throughput would then be scaled with available average power rather than scanning speeds. The types of laser process that may benefit from this include laser material process (marking/engraving/machining), lithography, and selective laser melting for 3D printing.

Project Proposal

The currently perused concept is to take a low power beam, shape it using conventional solutions such as spatial light modulators, and then pass it through an appropriately designed optical amplifier.

Somewhat of a literal translation of such an approach, using bulk amplifiers have been demonstrated in the past, but suffers from the usual issues of single pass bulk amplifiers, such as the incompatibility between high gains and gain nonlinearity. This project focuses on a novel design for an optical amplifier that can offer compatibility between high powers and high resolutions.



Precision Metrology for Large Freeform Non-Specular Surfaces

James Norman | Email: j.p.norman@cranfield.ac.uk | Sponsor: Hexagon Manufacturing Intelligence

Currently, there is not a standard method for measuring a metre–scale non-specular freeform surface in the 'ultra-precise' measurement regime; specifically, surface features in spatial frequency bandwidths lower than surface roughness. It is critical for manufacturing metrology to determine why this is, and produce measurement systems with the required specifications for ultra-precise measurement of these surfaces.

Of the state-of-the-art metre–scale non-specular surface measurement systems, there is not one method that fulfils the requirements of: high measurement accuracy and resolution, high measurement density, high speed, large measurement volume, and low cost. A system design with these characteristics is essential for the low uncertainty measurement, and subsequently, the production of precise components such as metre–scale optics for the next generation of extremely large telescopes as well as similarly sized optics for large laser systems.

An important example of metre–scale non-specular surfaces, with complex topologies, that require measurement with low measurement uncertainty are optics for large science projects such as ground–based and space telescopes for astronomy as well as high power laser systems for fundamental physics research. At several stages during manufacture these optics require such measurement, despite the non-specular nature of the measurand surfaces.

The current expectation for ultra-precise measurement of surfaces, post-grinding, involves a non-corrective polishing treatment designed to render the optical surface specular and measurable with an optical interferometer at a visible wavelength. This neutral polishing step has no affect upon the surface error in anything other than high spatial frequency bandwidths. Whilst this process enables the use of a highly accurate measurement method, given that the process has no direct effect on the figure error, it could be considered as inefficient; the process of neutral polishing and interferometry is expensive in materials, machining time, and measuring time.

This PhD project will endeavour to determine and implement a method for the measurement of metre–scale non-specular freeform surfaces, with uncertainty significantly lower than the current state-of-the-art measurement systems, capable of measuring such surfaces.

A new coordinate measurement system is being developed to measure these surfaces with uncertainty equivalent to standard displacement interferometry. The system utilises a number of laser trackers operated in displacement interferometry mode to determine the coordinates of a stylus moving over a metre-scale surface using a multilateration technique. This technique is illustrated in Figure 1.

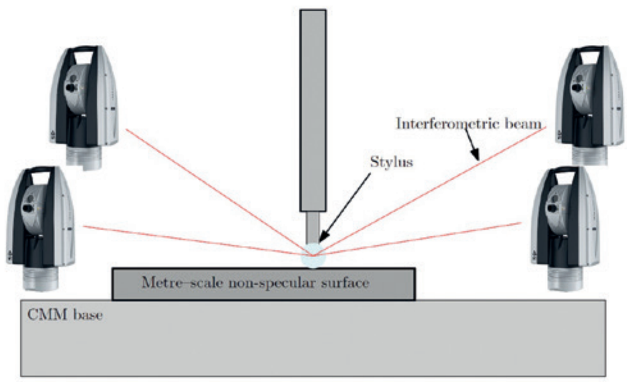


Figure 1. A number of laser tackers following the stylus tip of a large CMM as it moves over the surface of a metre-scale telescopic mirror segment.

Case Studies

1 Ultra-Precision Diamond Fly Cutting System

Industrial Partners:
Aerotech, Loxham Precision, Mitsubishi, Renishaw plc

Manufacturing highly flat components is a vital demand for the production of ultra-precision slideway components. An approximate technique to produce slideway components is by diamond fly cutting. However, very few machine tool companies make large scale diamond fly cutting machines and those companies that do produce them have very long lead times.

The development of the meso scale platform highlighted a limitation in the UK of being able to source large cuboid shape parts to high levels of accuracy. Parts over 500mm by 250mm could not be cost effectively produced in the UK with tolerances less than 5 micrometres.

It was therefore decided to produce a large scale diamond fly cutting machine within the Centre. An 80 day student group project, supervised by Professor Paul Shore and Keith Carlisle of **Loxham Precision** was undertaken. The project had three other supporting industrial partners:

Aerotech (UK) provided CNC and linear motors

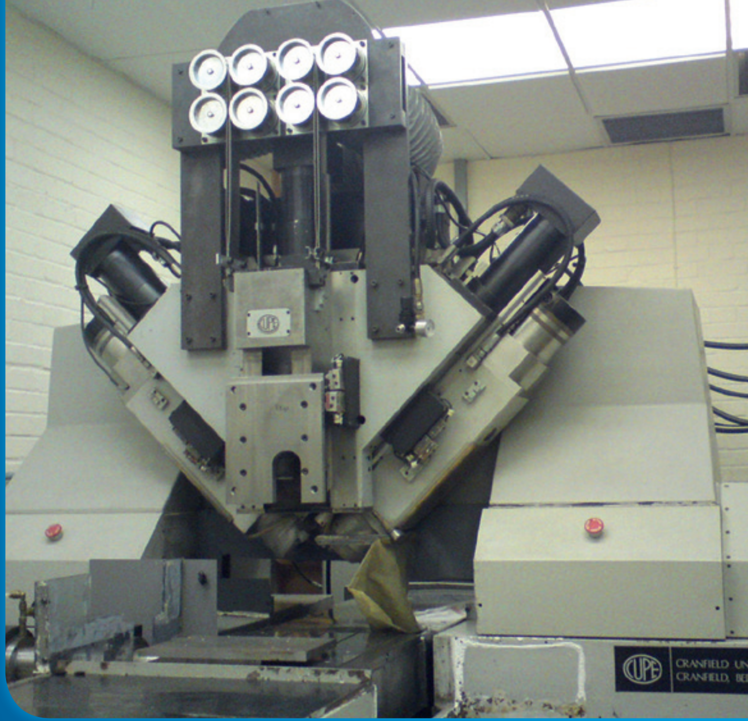
Mitsubishi (UK) provided spindle drive amplifiers

Renishaw plc provided linear measuring encoders

Georgios Zaganas, Sammy Yassine, Domenico Siniscalco, Hangtian Zhou and Quentin Bonnardel were 5 MSc students at **Cranfield University** who were tasked with building a large scale diamond fly cutting machine. It was specified such that it would be capable of producing large scale parts for the meso scale research platform.

The students were provided with a 40 year old machine tool as the basis for creating the new large scale diamond fly cutting machine.

The design, development, conversion and build of the machine through the group project is best understood through the student group project video:
https://www.youtube.com/watch?v=ph4yYxQeItE



Machine tool prior to the start of the group project

The critical learning outcome for the students was how to work in a team on a highly multidisciplinary project with a clear delivery requirement and short timescale. The output machine with further development undertaken by **Loxham Precision** has resulted in a large scale ultra-precision diamond machine tool. This machine tool is now used for the machining of critical air bearing component parts of the commercialised version of the meso scale research platform.

Machine post group project

2 Watch it Made®

Partners:

Royal Academy of Engineering Ingenious Scheme, Vauxhall Motors, National Physical Laboratory, Department for Business, Energy and Industrial Strategy

Supporting Industrial companies:

Hexagon Metrology, Contour Fine Tooling Ltd, Fusing Creativity Ltd

Enthusing pre GCSE aged children into studying engineering and related subjects is a long debated topic. The Centre's educational programme Watch It Made® was created to respond to this difficult matter. The national need being targeted was the lack of UK children prioritising the engineering profession.

The basic idea was to create a manufacturing experience that young learners would find fun, learn some practical skills and gain the pride of producing a useful product: a self-designed watch.

The manufacturing learning should bring about awareness of basic manufacturing processes and provide a personal experience of assembling a project. Critically, the "pride of producing" for oneself was emphasised.

Three MSc student group projects were undertaken within the Centre to create the Watch It Made® educational experience. These 80 day student group projects were supervised by Professor Paul Shore and Dr Paul Comley. Two of the group projects were performed at Cranfield and the first at Cambridge.

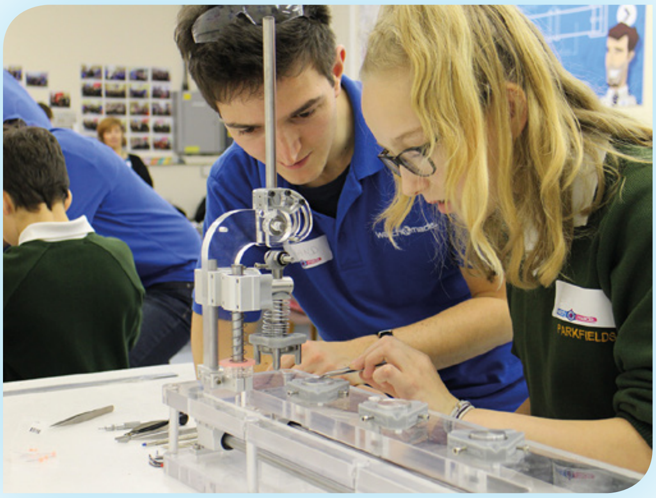
The second group project is best illustrated through their group project video:
https://www.youtube.com/watch?v=kNltngtmihI

Vauxhall Motors were so impressed they provided a Watch It Made® branded van to enable the Watch It Made® experience to go mobile.

After undertaking the Watch It Made® experience with 5-10 local schools (~75 children) the "learning by doing" and "pride in producing" aspects of the Watch It Made® experience gained broad support.

The **Royal Academy of Engineering** provided its support and with additional engineering companies also funding their local schools to attend, over 600 school children (> 25 schools) undertook the experience at the Watch It Made® Learning Studio at **Cranfield University**.

First cohort of pupils undertaking the watch making experience at Cranfield with the group project team



Assembly station

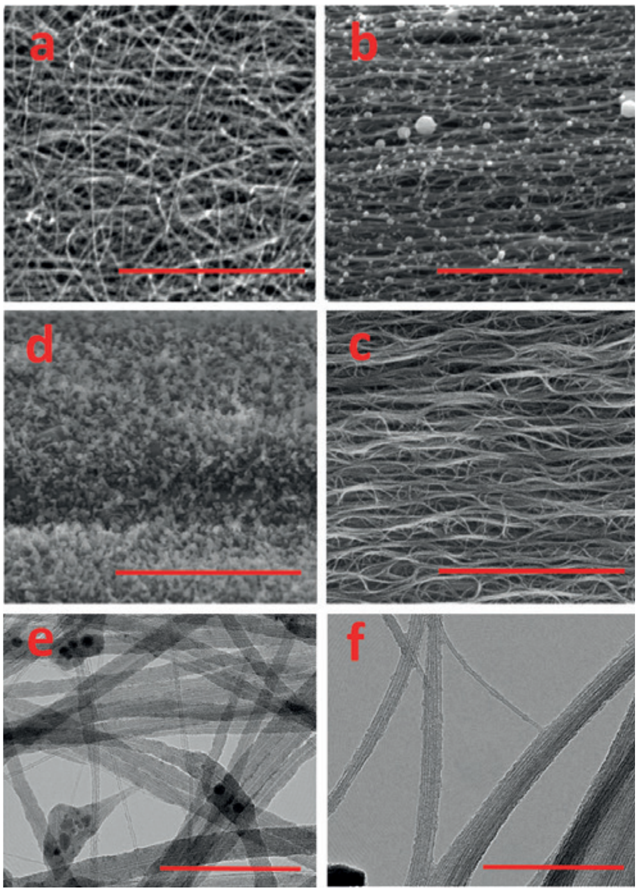
The Watch It Made® experience was also demonstrated at the **Glasgow Science Centre** during the *3rd Annual EPSRC Manufacturing the Future Conference* and the *Cambridge Science Festival* on two occasions. During 2016 the experience was run at the **National Physical Laboratory** in Teddington with over 100 children attending and making their own watches.

By the end of the EPSRC centre funding programme the **National Physical Laboratory** had offered to deliver the Watch It Made® programme through its Engineering Apprentice Programme, whilst other methods to continue the Watch It Made® experience were in planning at **Cranfield University**.

3 Ultra Precision Processing of Carbon based Materials

As part of the application of the ultra precision laser platform funded through the EPSRC Centre's research portfolio, and supported by students via the Centre for Doctoral Training in Ultra Precision Engineering, staff at the **University of Cambridge** have been researching laser processing of carbon nanotube (CNT) fibres in order to establish new manufacturing technologies for carbon based electrical systems.

CNT fibres are an important class of materials that show much promise in future electrical and mechanical applications. Early work focused on using the ultrafast laser platform to fashion CNT fibre bundles to enhance their field emission properties. Field emission (FE) cathodes are an appealing alternative to thermionic cathodes due to significant reduction in power requirements for such operating devices. Power reduction in the FE devices also offers an opportunity to reduce the size of the cathode device significantly. These demands have driven the research of FE or "cold" cathode technologies.



Figures a,b,c,d,e and f: representative scanning electron microscopy photographs at 5 kV of the CNT material through various stages of the photonic process. The red bar indicates 2 µm. (a) as-is CNT textile and (b) directly after atmospheric photonic processing. (c) removal of the residual catalyst with an acid wash. (d) even under inert conditions, too high of a laser fluence transforms CNTs into amorphous carbon. (e), (f) transmission electron microscopy images where the red bars indicate 100 nm. (e), as-is material showing individual double wall CNTs, multiwall CNTs, and malformed carbon species. (f) after photonic processing all that remains is exclusively isolated double wall CNTs and FWCNT bundles.

This work produced significant gains and received further inward investments from the **USAF** in order to explore the potential of CNT fibre bundles through a **USAF** funded grant [FA9550-14-1-0070] carried out at the **University of Cambridge** and the **Wright Patterson Air Force** base. The interaction of high power laser light was explored for the enhancement of field emission from CNT fibre[1]. A compound cathode made from four laser-patterned CNT films stacked together emitted greater than 8 mA of current. The CNT cathodes analysed in this study showed considerable promise by demonstrating the potential for scalability into large area arrays that could be used to generate the high current densities required for advanced device development in application areas such as field emission displays, high power microwave generators, and compact x-ray sources.

Further work on laser processing of CNT fibres focused on the enhancement of their electrical conductivity. A photonic based manufacturing methodology was developed, particularly suited for CNT fibre based textiles that selectively removes defective CNTs and other carbons not forming a sufficient thermal pathway. This is accomplished by rastering; a laser beam quickly moving along the surface. This results in a localised, translating oxidative flash where the material that survives is an optically transparent few walled CNT film with profound improvement in microstructure alignment and crystallinity[2]. The combined efforts in this area have led to a UK patent application for the photonic (laser) processing of CNT fibres for enhanced electrical properties[3]. x10 improvement in specific electrical conductivity through laser annealing under various non optimised conditions (5-50W cm^{-2}) with multiple wavelengths (1-10 um) was demonstrated. Researchers are seeking to improve on this performance through a systematic study of laser parameters and doping with charge transfer agents. It is believed that a scalable, post-treatment process such as the one developed at Cambridge has the potential to deliver CNT fibres that can be engineered for a wide range of electrical power transmission applications that have the potential to access multi-£billon markets for next generation products.

In addition to materials and applications development, engagement has been extended to the development of instrumentation technologies for the production of these carbon nano films and wires. CNT wires are a significant development in the field of carbon based materials and as such need to have their production technologies developed into effective manufacturing systems. The potential of this ground breaking process for making high-performance fibres with good conductivity or mechanical strength has led to considerable worldwide interest from a broad range of industrial sectors. It offers a disruptive technology that, if successfully developed for large-scale production, is poised to replace traditional materials in a host of mechanical and electrical applications. Moreover, the current research position established at Cambridge offers a significant opportunity for the UK to take the lead in the development of a new materials supply chain, new manufacturing process technologies, and product innovations that are a step change from their conventional counterparts.

This work has led to further research investments including an EPSRC Manufacturing the Future Award (EP/M02086X/1): Instrumentation and Control of Carbon Nanotube Fibre Manufacture, valued at £910,587, to be undertaken from May 2015-April 2018, in addition to collaboration with a range of industrial partners including **Dyson**, **Trumpf**, **Brokenhust**, and **Elektron Technologies Ltd**.

[1] S. Fairchild, et al. "Field emission from laser cut CNT fibers and films", Journal of Materials Research, Volume 29, Issue 03 2014, 392-402. [2] J. Bulmer et al, "Photonic sorting for aligned, crystalline, and conductive nanotube textiles", submitted to Nature Communications, February 2017. [3] J. Bulmer et al, "Carbon nanotube material, method for production and treatment of the same", UK patent application No 1700930.0, Feb 2017.

4 µ4 Ultra Precision Machine Range

The meso scale research platform has now progressed to become a product of the Cranfield spin out company **Loxham Precision**: the µ4 range of ultra precision machine tools.

The original concept of the meso research platform was conceived through a European Framework Project in 2006. It was advanced in regards a number of sub-systems through the EPSRC Integrated Knowledge Centre in Ultra Precision and Structured Surfaces. A basic operational concept machine was established by 2011.

Researchers and students of the EPSRC Centre for Innovative Manufacturing in Ultra Precision advanced the critical performance of novel small sized ultra precision motions of the meso scale research platform. These motion advancements have made this highly integrated and easily transported machine concept a viable and competitive multi-axes precision machine tool proposition.

After agreeing a commercialisation agreement with **Loxham Precision**, the Centre ran a competitive tender for the delivery of a meso scale ultra precision machine. Whilst international competitors did bid, the Loxham offer based around the Cranfield invented compact machine tool concept was independently assessed as the preferred vendor.

In parallel, **Loxham Precision** won an **Innovate UK** project in the field of automation of manufacturing systems. This project saw **Loxham Precision** develop automation technology that enables a 4 axes version of the µ4 to produce infrared optics with higher productivity potential. This **Innovate UK** project was carried out by **Loxham Precision** in partnership with **Qioptiq**, **Aerotech UK** and **Hexagon Metrology**.

Centre for Doctoral Training

The Cambridge and Cranfield Centre for Doctoral Training in Ultra Precision Engineering (CDT-UP) builds upon the recent research outputs from Cambridge and Cranfield Universities in order to develop a world leading training and research environment that delivers highly skilled ultra precision engineers to industry, capable of making a significant impact to the way in which UK manufacturing enterprises generate wealth utilising a new generation of ultra precision production technologies and products.

The CDT-UP is located at the heart of one of the most innovative regions in the world, where research activities are focusing on new production technologies and next generation products. By drawing on leading research competencies, we have created a wealth of state-of-the-art ultra precision laboratories and the research platforms that have been developed through a large number of research investments including the EPSRC Centre for Innovative Manufacturing in Ultra Precision. We have developed an advanced training and research experience that equips the next generation of manufacturing leaders and are uniquely placed within the UK to deliver this new form of training. We have exceptional research strengths in multidisciplinary fields, an outstandingly successful knowledge transfer environment, high levels of industrial engagement and a record of attracting first class science and engineering students.

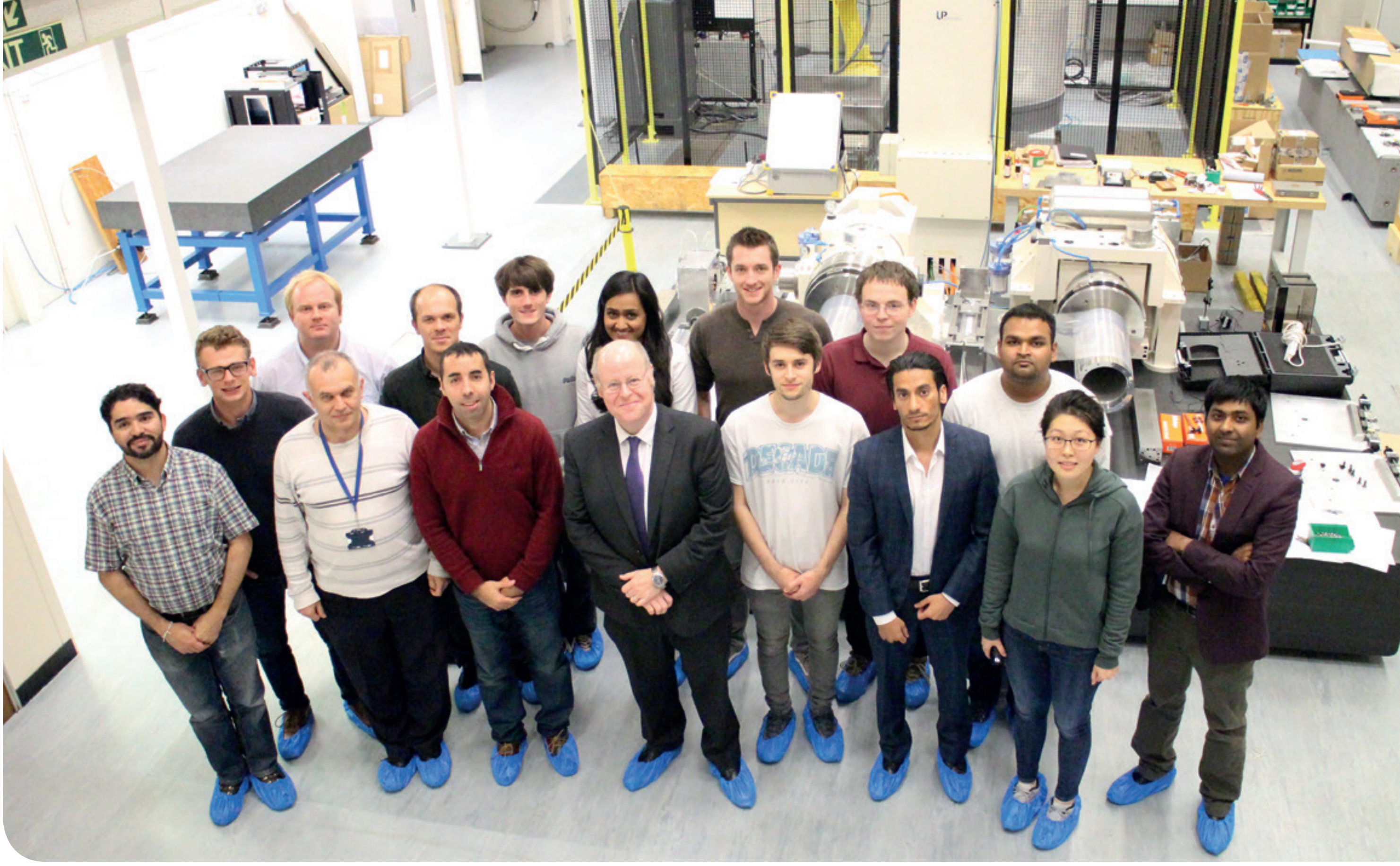
Our CDT-UP graduates possess the technical expertise and business skills required to take UK manufacturing companies into the top tier of global performance in ultra precision. Cambridge and Cranfield Universities have strong track records in supporting industry, with our PhD students developing highly successful careers in world leading companies. The beneficiaries of this Centre for Doctoral Training stretch across the whole of the EPSRC remit. All of the first cohort have been employed in national and international companies, and many of the current students are sponsored by national and international government, military, and commercial enterprises. The CDT-UP is fully aligned with the EPSRC Manufacturing the Future Programme since the strategic beneficiaries of the CDT-UP include a wide range of manufacturing enterprises including those involved in medical devices, consumer electronics, computing, defence technologies, communications, energy generation and security sectors.

The CDT-UP undertakes early stage production research and has established advanced manufacturing technologies pivotal to the creation of emerging products. Through close interaction with UK precision manufacturing supply chains, the UK's emerging product developers and leading UK universities, the CDT-UP has established an ultra precision research centre of national and international significance. The CDT-UP students have a unique opportunity to study in world-class facilities and are taught by world leading experts. The CDT-UP not only generates a source of invention and innovation, it encourages its graduates to hone their skills and apply them in our proven collaborative research environment. Thus, the CDT-UP, in partnership with industry, national and international government agencies, and other UK universities, has the capacity to play a significant role in helping its high calibre graduates maximize their potential to benefit society and the economy. The CDT-UP engages with other UK universities by providing them the opportunity to benefit from the outputs of the MRes training programme, with around 2 PhD studentships per year being made available to the wider ultra precision community, thereby supporting the emergence of a UK ultra precision network.

The CDT-UP has established a four year programme; a one year taught MRes course followed by three years of PhD research, assuming a suitable level of attainment in the very demanding MRes programme. We have worked hard to create the CDT-UP brand through a highly effective and well managed web based portal, community engagement through science festivals, hands on outreach activities such as the Watch it Made® educational programme, and an annual CDT-UP student lead research conference and exhibition that showcases the achievements of the Centre.

After a slow start due to lack of awareness of the ultra precision field by many graduates, we now have a strong demand from high quality UK students and self-funding international students. The CDT-UP has attracted a wide range of industrial sponsors with funding to enhance student stipends with an additional £10k per year over the three years of their PhD research. This support makes our applications process highly competitive and ensures that we admit only

PhD researchers and MRes students from Cambridge, Cranfield and Nottingham Universities



Cambridge and Cranfield 2016 MRes cohort with Cranfield University staff

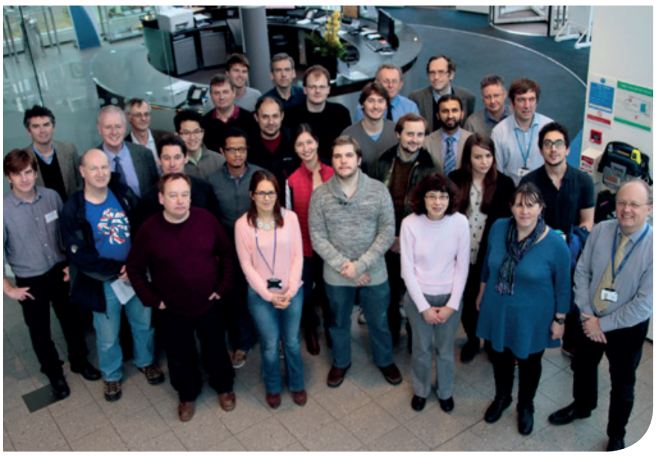
the best students whilst giving their research strong industrial relevance.

We offer a very rich and varied research training, research discovery and educational experience. The educational backgrounds of our students is broad, encompassing all of the major scientific and engineering disciplines. We have established a growing collection of committed industrial collaborators that receive research support relevant to their future industrial need and human capital requirements. We have established ground breaking technology outputs and made significant advances in the field of ultra precision engineering. The EPSRC CDT model is light years away from the old EPSRC PhD project studentships. We see our CDT students achieving more at a faster rate. They are highly sought after by employers and should deliver much greater impact to the UK economy.

In addition to modules delivered at Cambridge and Cranfield Universities, the first *Fundamentals of Metrology* module was delivered at the **National Physical Laboratory** over four days in January 2016. The lecture series was presented by seventeen NPL researchers and senior staff who are actively engaged in delivering metrology at the highest levels of accuracy and ensure international compatibility and traceability of the UK national measurement system.

Broad topics were covered throughout the course and students participated in laboratory tours of the mass, dimensional and thermal laboratories at NPL where they were able to see examples of primary metrology instruments used at NPL for performing measurements at the highest level of the traceability chain. They also saw the UK national copies of the prototype metre and kilogram artefacts, leading edge research into developing new metrology tools and progress towards the new International Systems of Units through NPL's work on the watt balance and the measurement of the Boltzmann constant.

Feedback from the course has been very positive and will be re-run yearly for the next few years as new cohorts of students join the CDT.



Cambridge and Cranfield students with staff from the National Physical Laboratory during the *Fundamentals of Metrology* module delivered in January 2016.

Awards and Prizes

The researchers across Cambridge and Cranfield Universities were successful in winning numerous awards and prizes throughout the duration of the programme.

2013

Krste Pangovski, PhD researcher at the **University of Cambridge** won the **CIRP sponsored best presentation award** for his for his presentation "Digital holograph analysis of laser induced micro plasma in micro machining applications: temporal and spatial comparisons to thermos nuclear explosions" at the *2nd Annual EPSRC Manufacturing the Future Conference*, 17-18 September 2013, Cranfield University, UK.

2014

Jake Larsson, PhD researcher at **Cranfield University** won the **Autocar-Courland Next Generation Award** of £7,500. This award was provided by 6 automotive companies and provided Jake with a 1 month duration work experience session at each company including **Jaguar Land Rover** and **McLaren**.

Jon Parkins, PhD researcher at the **University of Cambridge** was awarded the **Leete Premium Award** from the **Worshipful Company of Engineers** in support of his PhD studies.

Andrew Payne, PhD researcher at the **University of Cambridge** was winner of the Department of Engineering's annual photo competition sponsored by **Zeiss**. Andrew won the Head of Department's prize for his video of the rise and fall of liquid crystal "mountains" made from a collection of images taken an one second intervals.

Jon Parkins and **Tianqi Dong**, PhD researchers at the **University of Cambridge** took part in the *First Year PhD Conference* in May 2014, organised by first year PhD students at the **Institute for Manufacturing**. Jon was the poster winner at the conference and Tianqi came joint second.

Jonathan Abir, PhD researcher at **Cranfield University** took part in the *eu**spen** Challenge* in July 2014 hosted by **HEINDENHAIN GmbH** in Traunreut, Germany. He was part of the winning team who were awarded Best Presentation and Most innovative Solution.

Tianqi Dong, PhD researcher at the **University of Cambridge** attended the *4th International School on Lasers in Materials Science (SLIMS)*, held in July 2014 in Venice, Italy and came third place to win the Roger Kelly Award for Best Young Research Presentation.

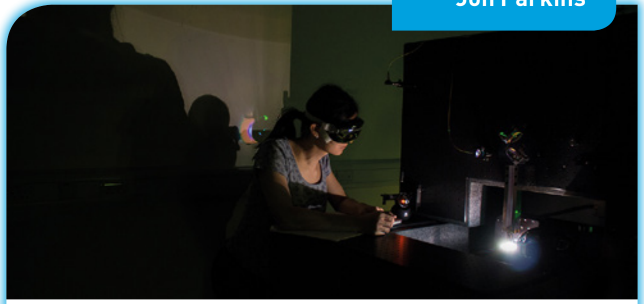
2015

Tianqi Dong, PhD researcher at the **University of Cambridge** won first prize for her paper "Evaluating femtosecond laser ablation of graphene on SiO2/Si substrate" at the *International Congress on Applications of Lasers & Electro-Optics (ICALEO)*, held in October 2015 in Atlanta, USA.

Andrew Payne, PhD researcher at the **University of Cambridge** was again one of the winners of the Department of Engineering's annual photo competition sponsored by **Zeiss**. Andrew won second prize for his image of a titanium "comet".

2016

Jon Parkins



Jon Parkins, PhD researcher at the **University of Cambridge** won the *EPSRC Science Photo Competition 2015*, an event for all **EPSRC** supported researchers and **EPSRC** supported doctoral students to share their research using images. Jon's winning photo *"where there is light, there is shadow"* is shown above. Jon said:

"The image shows engineering PhD student Karen Yu working on the ultra-precise ultrafast laser system developed by the EPSRC Centre for Innovative Manufacturing in Ultra Precision. Extremely small, well controlled features can be created using ultrafast light pulses. These light pulses occur on a timescale faster than heat can pass between the atoms of the material, resulting in very little heat damage to the surrounding areas.

In this image, a piece of glass is being processed with a high power ultrafast laser. This causes very bright plasma to form. The glass block channels the light through its sides resulting in a bright white glow emanating from the processing area which casts shadows around the room.

This image was captured in the labs at the Institute for Manufacturing, Cambridge using a Canon 70D. Photoshop was used to adjust brightness and contrast."

Nan Yu

Nan Yu, PhD researcher at **Cranfield University** won the *Best Doctoral Student Ambassador in Manufacturing 2016* award. **Cranfield University** recognises that its students and alumni are its best ambassadors making the time spent here memorable and academically worthwhile. The Manufacturing Department wanted to reward the best doctoral student and called for nominations from both staff and students.

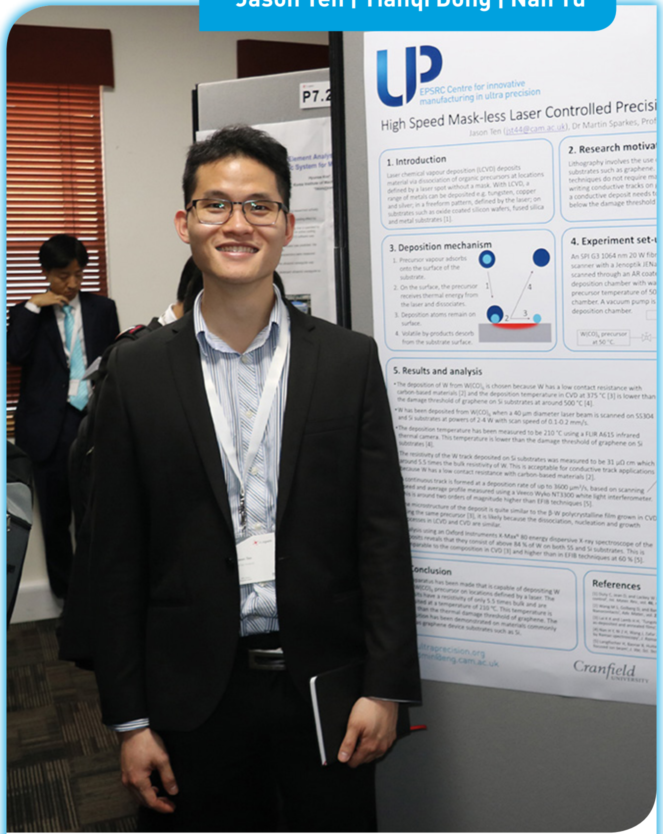
Nan was delighted to hear that he had won the award and was presented with his certificate and prize at a special alumni dinner where Cranfield also welcomed distinguished guests and alumni to the *National Manufacturing Debate* held at Cranfield on 25 May 2016.

Nan said, *"I am so pleased to win the best research student ambassador award. Receiving this award is such an amazing honour and a fantastic memory of my life at Cranfield. I never thought I would win it, and I couldn't have done it without you all. Thank you very much for your support, help and encouragement."*

Adam Bennett

Adam Bennett, PhD researcher at **Cranfield University** was awarded a *Santander Mobility Award* in 2016 for innovative research. The award enabled Adam to present and publish his research at the *27th Symposium on Plasma Physics & Technology*, 20-23 June 2016 in Prague, Czech Republic.

Jason Ten | Tianqi Dong | Nan Yu



Jason Ten, first prize winner of the poster session

PhD researchers across both campuses attended the *16th International Conference and Exhibition of the European Society for Precision Engineering and Nanotechnology* in June 2016. **Jonathan Abir** from **Cranfield University** was selected for an oral presentation and many posters were presented at the event. **Jason Ten** and **Tianqi Dong** both from the **University of Cambridge** won first and third prizes respectively in the poster session. **Nan Yu** from **Cranfield University** won a **Heidenhain** scholarship provided by eu**spen Ltd**, which contributed towards his registration and travel expenses, and was presented with his award at the conference by members of **Heidenhain** staff.

Nan accepting the Heidenhain Scholarship award

Jonathan Abir

Jonathan Abir at the ASPE 2016 Spring Topical Meeting

Jonathan Abir, a PhD researcher from **Cranfield University** had the opportunity to present his research 'Feedback based technique for improving dynamic performance of a small size machine tool' at the *American Society for Precision Engineering (ASPE) 2016 Spring Topical Meeting: Precision Mechatronic System Design and Control.*

The event organised by **ASPE**, took place at the **Massachusetts Institute of Technology**, Cambridge, Massachusetts, USA from 20 to 22 April 2016. This was the Society's 5th Topical Meeting in a series on the precision design and control of mechatronic systems. The meeting developed and promoted a broader understanding of the precision engineering principles of determinism for use in meeting the challenges posed by the design and control of high-performance mechatronic systems. It brought together specialists and practitioners from academia, industry, and government for the exchange of ideas and to identify topics of common concern for further research.

Jonathan was also successful in securing a travel award from the **Institution of Engineering and Technology** which aided his travel to present at the ASPE meeting.

IET AWARDS The Institution of Engineering and Technology | TRAVEL AWARD WINNER 2016

Clare Collins

Clare Collins, a third year PhD student at the **University of Cambridge** was awarded a Special Commendation in *The Royal Society Publishing Photography Competition 2016.*

Clare won her prize in the micro-imaging category. Seemingly a swarm of jellyfish, this image was created using carbon nanotubes grown in a pillar formation. The metal disks that make up the jellyfish bodies are made by 'sputtering' charged aluminium and iron ions onto a surface to deposit a thin film of the metals. The carbon nanotubes grow from this thin disk. The disks are 5 micrometers in diameter – 5 1/1000ths of a millimetre – and are 10 micrometers apart.

If you zoomed out of the image, you would be able to see that they make up part of a 2 mm x 2 mm pattern across the surface of a silicon chip. Clare researches carbon nanotubes to study the emission of electrons, called the field emission, from a number of different configurations. The applications for field emission could be for displays or as X-ray sources.

Quality and Metrics

	Target	Achieved at Year 5
Publications		
Journal papers 1 paper per 1 research staff person year	55	80
Keynotes given by Centre investigators and researchers 1 keynote given at international conference per 2 staff person years	25	26
Student keynotes /awards 1 student provided keynote or presentation award per 3 staff person years	8	10
Outreach		
Strategic outreach meetings 3 per year to establish UP Centre as UK hub	15	28
Development		
PhDs completed Directly funded by the Centre	16	4
PhDs completed Funded by the CDT in Ultra Precision	30	N/A
PhDs completed Incorprated students	N/A	2
Promotion of 40% of staff engaged in UP Centre	8	7
40% of PhDs to hold RA, engineer or science positions in UK	12	3
Partnerships		
Maintain original partners 75% still active after 5 years	3	3
Engage new industrial partners 2 per year	10	10
Uptake		
Centre main project taken forward by industry	3	3
Centre		
Planning and delivery Hold overall programme by delivering Gantt deliverables and milestones	22	20
Added value to UP Centre Secure additional funding equal to EPSRC original funding	£6.8m	£9.5m

Esteem

Journal Publications

Abir, J., Longo, S., Morantz, P. and Shore, P. (2016). *"Optimized estimator for real-time dynamic displacement measurement using accelerometers"*
Mechatronics, 39, 1-11. DOI: 10.1016/j.mechatronics.2016.07.003.

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de Podesta, M., Harris, P., Underwood, R., Sutton, G., Mark, D. F., Stuart, F., Morantz, P. and Machin, G. (2016). *"Response to Macnaughton's 'Comment on "A low-uncertainty measurement of the Boltzmann constant"'*
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de Podesta, M., Underwood, R., Sutton, G., Morantz, P., Harris, P., Mark, D. F., et al (2013). *"A low-uncertainty measurement of the Boltzmann constant"*
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Dong, T., Sparkes, M., Durkan, C. and O'Neill, W. (2016). *"Evaluating femtosecond laser ablation of graphene on SiO_2/Si substrate"*
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Presented abstract at the 2nd Annual EPSRC Manufacturing the Situtre Conference, 17-18 September 2013, Cranfield University, Bedfordshire, UK. This presentation won the CIRP sponsored best presentation award.

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J.Mec. Behaviour of Biomedical Materials, 60, 22–37.

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Tonnellier, X., Comley, P., Peng, X. Q. and Shore, P. (2013). *"Development of an industrial based robot based polishing platform for large optical components"*
Proceedings of the 3rd European Optical Society Manufacturing Optical Components, 13-15 May 2013, Munich, Germany.

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Proceedings of the 16th International Conference of the European Society for Precision Engineering and Nanotechnology, 30 May-3 June 2016, University of Nottingham, Nottingham, UK, 469-470.

Xu, H., Davey, A. B., Crossland, W. A. and Chu, D. P. (2012). *"UV durable colour pigment doped SmA liquid crystal composites for outdoor tran-reflective bi-stable displays"*
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Yu, K.X.Z., Sparkes, M. R., Pangovski, K. and O'Neill. W. (2016). *"Monitoring and closed loop feedback control of ultrafast glass welding"*
Proceedings of the 16th International Conference of the European Society for Precision Engineering and Nanotechnology, 30 May-3 June 2016, University of Nottingham, Nottingham, UK, 445-446.

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Proceedings of the 3rd Annual EPSRC Manufacturing the Future Conference, 23-24 September 2014, Glasgow, UK, 109.

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Proceedings of the 16th International Conference of the European Society for Precision Engineering and Nanotechnology, 30 May-3 June 2016, University of Nottingham, Nottingham, UK, 459-460.

Zhou, H., Jourdain, R., Serantoni, V., Endrino, J. L. and Shore, P. (2016). *"Creation of a control system for plasma delivery to increase determinism and robustness while processing using an ICP torch"*
Proceedings of the 16th International Conference of the European Society for Precision Engineering and Nanotechnology, 30 May-3 June 2016, University of Nottingham, Nottingham, UK, 261-262.

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User story in Speedgoat. https://www.speedgoat.ch/Portals/0/Content/UserStories/cranfield_user_story.pdf.

Caroff, F. and Didier, A. (2015). *"Watch it Made"*
WatchPro, February 2015, 32-35.

Leach, R. K. (2013). *"Thinking outside the Bento Box"*
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Leach, R. K. and Harris, P.M. (2012). *"SoftGauges for areal surface texture parameters"*
Quality Manufacturing Today, March 2012, 33-35.

O'Hara, M. (2015). *"Lasers merging industry and academia - Seminar on laser-based processes in ultra precision production"*
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O'Hara, M. (2015). *"What's UP? Ultra precision manufacturing in the UK"*
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Innovation into Success, 40, 61-64.

O'Hara, M. (2017). *"Legacy of the EPSRC Centre for Innovative Manufacturing in Ultra Precision – The Future of Precision Engineering: UK Perspective"*
Mikroniek, 57 (1), 30-34.

O'Hara, M., Young, C., Meuwese, M. and Pekelder, S. (2016). *"Report of eu**spen**'s 16th International Conference and Exhibition – Bigger, broader, better..."*
Mikroniek, 56 (3), 12-17.

Pangovski, K. and O'Neill, W. (2012). *"Designer laser pulses for materials processing"*
The Laser User, 67, 26-28.

Pangovski, K., Sparkes, M. and O'Neill, W. (2015). *"A new way to diagnose and optimise laser-material processing operations"*
The Laser User, 77, 16-17.

Yu, K. X. Z., Sparkes, M. and O'Neill, W. (2015). *"OCT and DHM - Control system for ultra precision processing"*
Mikroniek, 55 (5), 32-35.

Keynotes

Abir, J. (2015). *"Influence of temperature changes on a linear motion system"*
Laser Metrology, Machine Tool, CMM and Robotic Performance (Lamdamap 2015), 17-18 March 2015, Huddersfield, UK.

Bennett, A., Jourdain, R., Kirby, P., MacKay, P., Shore, P. Nicholls, J., Morantz, P. (2016). *"Microwaves enable activated plasma figuring for ultra-precision fabrication of optics"*
16th International Conference of the European Society for Precision Engineering and Nanotechnology, 30 May-3 June 2016, University of Nottingham, Nottingham, UK.

Chu, D. (2012). *"Novel materials for light and radiation control of green buildings"*
The Second International Materials Forum (IMF 2012), April 2012, Wuhan, China.

Chu, D. (2012). *"Smectic A based nano-materials for energy efficiency of the built environment"*
World Congress on Nano Sciences and Technologies 2012, October 2012, Qingdao, China.

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.

Leach, R. (2013). *"Determination of the lateral resolution of two commercial surface topography measuring interferometers"*
The 11th International Symposium on Measurement Technology and Intelligent Instruments (ISMTII 2013), 1-5 July 2013, Germany.

Leach, R. (2013). *"Metrology challenges for highly parallel micro-manufacture"*
4M 2013, 8-10 October 2013, Spain.

Leach, R. (2013). *"Surface metrology challenges for advanced manufacturing"*
The 3rd International Conference on Manipulation, Manufacturing and Measurement on the Nanoscale (3M-NANO), 26-30 August 2013, China.

Leach, R. (2014). *"High dynamic range surface metrology"*
nano-Man 2014, 8-10 July 2014, Bremen, Germany.

Leach, R. (2014). *"Multi-scale characterisation of laser textured surfaces"*
The Association of Laser Users Micro Nano SIG, 17 September 2014, Birmingham, UK.

Leach, R. (2014). *"On-line surface metrology challenges"*
International Symposium on Precision Engineering and Instrumentation (ISPEME 2014), 8-11 August 2014, Changsha, China.

Leach, R. (2014). *"Traceability for areal surface topography measurements"*
International Conference on Microscale Morphology of Component Surfaces (MICOS), 13-14 February 2014, Germany.

Morantz, P. (2012). *"Multi-process strategy for freeform optics manufacture"*
3rd International Conference on Nano manufacturing (nanoMan 2012), 25-27 July 2012, Tokyo, Japan (invited keynote).

Morantz, P. (2014). *"Manufacturing machine automation and precision capability"*
20th International Conference on Automation and Computing (ICAC 2014), 12-13 September 2014, Cranfield, Bedfordshire, UK (invited keynote).

Morantz, P. (2015). *"The μ4 diamond machining system"*
Laser Metrology, Machine Tool, CMM and Robotic Performance (Lamdamap 2015), 17-18 March 2015, Huddersfield, UK (invited keynote).

O'Neill, W. (2013). *"Laser processing of graphene"*
Cambridge Graphene Tech Day, 6 November 2013, University of Cambridge, UK.

O'Neill, W. (2014). *"Ultra precision manufacturing challenges, opportunities and industrial outlook"*
Catalysis Conference, April 2014, Downing College, Cambridge, UK.

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

O'Neill, W. (2015). *"Additive manufacturing, a technology set of change?"*
The Industrial Laser Applications Symposium 2015, 17-18 March 2015, Chesford Grange Conference Centre, Kenilworth, Warwickshire, UK.

O'Neill, W. (2015). *"Manufacturing at the speed of light"*
Keynote Lecture for the Society of European Students of Industrial Engineering and Management, 8 January 2015, Institute for Manufacturing, University of Cambridge, UK.

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

Parkins, J., Jourdain, R., Marson, S., Shore, P., Sparkes, M. and O'Neill, W. (2012). *" Laser assisted plasma processing: an overview"*
12th International Conference and Exhibition of the European Society for Precision Engineering and Nanotechnology, 4-8 June 2012, Stockholm, Sweden.

Sansom, C. (2014). *"Sol gel anti-reflective coatings and thin film solar collectors for CSP applications in desert environments"*
XTremeCoat, 20-21 October 2014, Madrid, Spain.

Shore, P. (2012). *"Ultra-precision enabling our future"*
14th International Conference on Precision Engineering (ICPE 2012), 8-10 November 2012, Awaji Yumebutai International Conference Center, Hyogo, Japan.

Shore, P. (2013). *"Precision manufacturing – current status and future development"*
3rd International Conference on Advanced Manufacturing Engineering and Technologies (NewTech 2013), 27-30 October 2013, Stockholm, Sweden.

Shore, P. (2014). *"Rapid fabrication of advanced optics – 1 foot^2 per hour"*
Mirror Technology Days 2014, November 2014, Albuquerque, New Mexico, USA.

Shore, P. (2014). *"Thermal issues, past and present"*, eu**spen** Special Interest Group: Thermal issues, 19-20 March 2014, Zurich, Switzerland.

Shore, P. (2015). *"μ4 – a compact 6 axes ultra-precision micromachining system"*
6th International Conference of the 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.

Conference Presentations

Abir, J., Morantz, P. and Shore, P. (2014). *"Design and control of a compact ultra-precision machine for high dynamic performance"*
12th International Conference on Manufacturing Research (ICMR 2014), 9-11 September 2014, Southampton, UK.

Bennett, A., Jourdain, R., Kirby, P., MacKay, P., Shore, P. Nicholls, J., Morantz, P. (2016). *"Microwave generated reactive plasma for ultra precision engineering of optics"*
eu**spen** Special Interest Group: Structured & Freeform Surfaces, 9-10 November 2016, Technical University of Denmark, Copenhagen, Denmark.

Bennett, A., Jourdain, R., Kirby, P., MacKay, P., Shore, P. Nicholls, J., Morantz, P. (2016). *"Microwave generated reactive plasma for ultra precision technologies"*
27th Symposium on Plasma Physics, 20-23 June 2016, Prague, Czech Republic.

Barrington, J. (2016). *"A precision fibre optic CO_2 sensor for gas analysis"*
Rising Stars in Gas Sensing: the Early Career Researchers Meeting – 64th Gas Analysis and Sensing Group Colloquium, 21 April 2016, Cranfield University, Bedfordshire, UK. (poster presentation).

Chu, D. (2012). *"Laminated electro-active foils for the built environment"*
Large Area Electronics: Addressing the Applications Challenge, 18 December 2012, Cambridge, UK (invited presentation).

Chu, D. (2012). *"UV durable colour pigment doped SmA liquid crystal composites for outdoor trans-reflective bi-stable displays"*
Organic Photonics and Electronics – Liquid Crystal XVI, August 2012, San Diego, USA.

Chu, D. (2013). *"High brightness reflective display to light and radiation control of green buildings"*
EuroDisplay 2013, 16-19 September 2013, Imperial College London, London, UK (invited presentation).

Chu, D. (2013). *"Novel siloxane based smectic A liquid crystal materials: formulation, structures and optical device applications"*
Organic Photonics and Electronics – Liquid Crystals XVII, August 2013, San Diego, USA (invited talk).

Chu, D. (2013). *"Printed electronics – how to make transistors and displays from liquid source materials"*, 4th Printed Electronics China (PE China 2013), 25-26 September 2013, Suzhou, China (invited talk).

Dong, T. (2014). *"Femtosecond laser direct micro-cutting of graphene for device applications"*
Graphene & 2D Materials Conference: From Research to Applications, 12-13 November 2014, London, UK.

Dong, T. (2015). *"Evaluating femtosecond laser ablation of graphene on SiO_2/Si substrate"*
International Congress of Applications of lasers & Electro-Optics (ICALEO 2015), 18-22 October 2015, Atlanta, USA.

Dong, T. (2015). *"Laser processing of graphene for device application"*
brainSTEMS, 19 November 2015, Lucy Cavendish College, Cambridge, UK.

Jourdain, R., Suder, W. and Williams, S. (2015). *"An approach for laser finishing of wire+ arc additive manufacturing components"*
Laser Processes in Ultra Precision Manufacturing, 15 October 2015, Ricoh Arena, Coventry, UK. (invited presentation).

King, P., Comley, P. and Sansom, C. (2013). *"Parabolic trough surface form mapping using photogrammetry and its validation with a large Coordinate Measuring Machine"*
19th SolarPaces Conference, 17-20 September 2013, Las Vegas, USA.

King, P., Comley, P. and Sansom, C. (2013). *"The characterisation of CSP parabolic mirrors using photogrammetry"*
3rd EOS Conference on Manufacturing of Optical Components (EOSMOC 2013), 13-15 May 2013, Munich, Germany.

Morantz, P. (2012). *"Introduction to optical surface engineering"*
Workshop on the Future of Particle and Energy Beam Processes for Optical Manufacturing in Europe, 29 August 2012, Royal Society, Chicheley, Buckinghamshire, UK. (invited presentation).

Morantz, P. (2013). *"Concept design, development and realisation of a compact multi-process diamond machining system"*
Review of Ultra Precision and Structured Surfaced Integrated Knowledge Centre, 20 June 2013, Royal Academy of Engineering, London, UK (invited presentation).

Morantz, P. (2013). *"Dynamically controlling the position and distortion of transparent flexible film (to microns)"*
Metrology Technologies to Enable Reel to Reel Processing of Emerging Products, 20 November 2013, National Physical Laboratory, Teddington, UK (invited presentation).

Morantz, P. (2013). *"Introducing Loxham Precision"*
13th International Conference and Exhibition of the European Society for Precision Engineering and Nanotechnology, 27-31 May 2013, Berlin, Germany.

Morantz, P., and Allsop, J. (2014). *"Establishing a large microstructuring roll diamond turning facility"*,
Structured and Freeform Surfaces 2014, 19-20 November 2014, Padova, Italy (invited presentation).

Morantz, P. (2015). *"Control of cooling and process fluids with traceable accuracy and multi-kelvin precision"*
High-Tech Systems 2015, 25-26 March 2015, 's-Hertogenbosch, Netherlands.

Morantz, P. (2015). *"Grinding and metrology of large freeform optics"*
Optical Demands of Astronomy, 16 June 2016, Edinburgh, UK (invited presentation).

Morantz, P. (2015). *"State of the art of very high precision measurements in metrology"*
1st Particle Accelerator Components' Metrology & Alignment to the Nanometre Scale (PACMAN) Workshop, 2-4 February 2015, CERN, Geneva, Switzerland (invited presentation).

Morantz, P. (2015). *"The µ4 diamond machining system"*
Roadmapping Workshop, Micro-Machining Research Platform, 22 April 2015, Cranfield University, Bedfordshire, UK (invited presentation).

Morantz, P. (2015). *"Ultra precision"*
4th Annual EPSRC Manufacturing the Future Conference, 17-18 September 2015, Cambridge, UK (invited presentation).

Norman, J. and Abir, J. (2016). *"From meso-scale to metre-scale machines – developments in position measurement technologies"*
Future Challenges of Instrumentation and Control in Ultra Precision Manufacturing, 18 May 2016, Renishaw plc, Gloucestershire, UK. (invited presentation).

O'Neill, W. (2012). *"Laser materials processing"*
Photonics Europe, 18 April 2012, Brussels, Belgium.

O'Neill, W. (2012). *"Supersonic laser deposition of hard facing materials"*
15th International Conference on Laser Optics, 27 June 2012, St Petersburgh, Russia.

O'Neill, W. (2012). *"Supersonic laser deposition of metals"*
1st Annual EPSRC Manufacturing the Future Conference, 19-20 September 2012, University of Loughborough, UK.

O'Neill, W. (2013). *"Additive manufacturing: innovation in materials and processes"*
Innovation in Materials, 11 November 2013, Royal Academy of Engineering, London, UK. www.youtube.com/watch?v=lzwMmL6lDYM.

O'Neill, W. (2013). *"Laser based additive manufacturing technologies"*
Laser Additive Manufacturing Workshop, 12-13 February 2013, Houston, TX, USA.

O'Neill, W. (2013). *"Manufacturing at the speed of light"*
26 November 2013, University of the Third Age, Cambridge, UK.

O'Neill, W. (2013). *"Preparing for the future at the IfM"*,
International Laser Forum, April 2013, Nottingham, UK.

O'Neill, W. (2014). *"Ultra precision technologies"*
Manufacturing Review, January 2014, Institute for Manufacturing, University of Cambridge, UK.

O'Neill, W. (2014). *"Working with the speed of light"*,
Speakers for Schools, 2 May 2014, Etonbury Academy, Arlesey, Bedfordshire, UK.

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.

O'Neill, W. (2015). *"Laser processing of carbon based nanomaterials"*
Photonics West 2015, 10 February 2015, San Francisco, CA, USA.

O'Neill, W. (2015). *"Ultra precision machining systems and technologies"*
Laser Processes in Ultra Precision Manufacturing, 15 October 2015, Ricoh Arena, Coventry, UK. (invited presentation).

O'Neill, W. (2016). *"3D printing of metals: Increasing productivity – The next big step"*
The Fourth World 3D Printing Technology Industry Conference and Expo, 31 May-2 June 2016, Shanghai, China.

Pangovski, K., Sparkes, M. and O'Neill, W. (2015). *"Investigation into the ablation mechanisms of titanium, aluminium, copper and brass in percussion drilling operations, using ultra-high speed digital holography"*
Laser Processes in Ultra Precision Manufacturing, 15 October 2015, Ricoh Arena, Coventry, UK. (invited presentation).

Sansom, C. (2012) *"CSP at Cranfield University, UK – Technical capabilities and knowledge transfer"*
EMIS forum on Solar Energy and Energy Efficiency (FORSEE) Program, 25-26 June 2012, Tunis, Tunisia.

Sansom, C. (2013). *"Precision Engineering for Concentrating Solar Power (CSP) applications"*
13th International Conference and Exhibition of the European Society for Precision Engineering and Nanotechnology, 27-31 May 2013, Berlin, Germany.

Sansom, C., Comley, P., Bhattacharyya, D. and Macerol, N. (2013). *"A comparison of polymer film and glass collectors for concentrating solar power"*
19th SolarPaces Conference, 17-20 September 2013, Las Vegas, USA.

Sansom, C., Comley, P., King, P., Almond, H. and Endaya, E. (2014). *"Predicting the effects of sand erosion on collector surfaces in CSP plants"*
20th SolarPaces Conference, 16-19 September 2014, Beijing, China.

Sansom, C. and Fernández-García, A. (2015). *"Contact cleaning of polymer film solar reflectors"*
21st SolarPaces Conference, 13-16 October 2015, Cape Town, South Africa.

Stravroulakis, P., Bointon, P., Southon, N. and Leach, R. (2016). *"Information rich approach to non-destructive non-contact measurement planning, inspection and verification for additive manufacturing"*
ASPE 2016 Summer Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing, 27-30 June 2016, Raleigh, North Carolina, USA. (poster presentation)

Turner, P. J. and Sansom, C. (2014). *"A tubed, volumetric cavity receiver concept for high efficiency, low-cost modular molten salt solar towers"*
20th SolarPaces Conference, 16-19 September 2014, Beijing, China.

Turner, P. J. and Sansom, C. (2015). *"Optimal spacing within a tubed, volumetric, cavity receiver suitable for modular molten salt solar towers"*
21st SolarPaces Conference, 13-16 October 2015, Cape Town, South Africa.

Yu, K. (2014). *"Control systems for ultra precision processing"*
3rd Annual EPSRC Manufacturing the Future Conference, 23-24 September 2014, Glasgow, UK.

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. (invited presentation).

Other Presentations and Publications

Cole, M. T., Collins, C., Parmee, R., Li, C. and Milne, W. I. (2015). *"Nanocarbon Electron Emitters: Advances and Applications"*
Chemical Functionalization of Carbon Nanomaterials, Chapter 45, 1035-1061.

Diaz, A. (2015). *"A brief introduction to ultra precision engineering"*
Presented to sixth form students at Stationers' Crown Woods Academy, 30 April 2015, London, UK.

Diaz, A. J., Docker, P., Axford, D., O'Neill, W., Evans, G., Sparkes, M., Cordovez, B., Fuglerud, S. and Stuart, D. (2016). *"The automation of nanoparticle sample delivery for protein crystallography experiments using an evanescent field optical tweezing technique"*
The 20th International Conference on Miniaturized Systems for Chemistry and Life Sciences (MicroTAS 2016), 9-13 October 2016, Dublin, Ireland. (poster presentation).

Morantz, P. (2014). *"Control techniques in ultraprecision"*
Aerotech UK New Premises Official Opening, 28 January 2014, Tadley, UK.

O'Hara, M. (2015). *"Large scale (1.4m 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, W. (2012). *"Advanced manufacturing: Lasers and their role in production"*
11 October 2012, The Wellington Academy, Tidworth, UK.

O'Neill, W. (2012). *"Working at the speed of light"*,
Cambridge Science Festival, 24 March 2012, Institute for Manufacturing, University of Cambridge, UK.

O'Neill, W. (2014). *"3D printing: the myths, the truths, the future"*
Summer School, 24 July 2014, Cambridge, UK.

O'Neill, W. (2014). *"Advances in laser based production technologies"*
Presentation made to the Institution of Mechanical Engineers at the Institute for Manufacturing, 6 March 2014, University of Cambridge, UK.

O'Neill, W. (2014). *"Advances in laser based manufacturing"*,
Institution of Mechanical Engineering, 6 March 2014, Institute for Manufacturing, University of Cambridge, UK.

O'Neill, W. (2014). *"Commercial implications of graphene"*
The Royal Institution of Great Britain, 2 December 2014, London, UK.

O'Neill, W. (2014). *"Graphene: the world changing nano material"*
How to: Academy, 8 July 2014, Condé Nast, UK.

O'Neill, W. (2015). *"High value manufacturing future jobs and opportunities"*
Talk to college students in the south west of London organised by Downing College, Cambridge, 10 April 2015, Deutsche Bank London, UK.

O'Neill, W. (2016). *"Laser based manufacturing"*
Speakers for Schools, Frederick Bremer School, Walthamstow, London, UK.

Shore, P. (2014-2015). *"Engineering or super heroes?"*
Vandyke Upper School, 15 July 2014, Leighton Buzzard, Bedfordshire, UK, Kimberley STEM College, 11 December 2014, Stewartby, Bedfordshire, UK and UTC Central Bedfordshire, 9 February 2015, Houghton Regis, Bedfordshire, UK.

Election to Learned Societies

Professor Paul Shore
Fellow of the Royal Academy of Engineering

Mr Adam Bennett
Fellow of the Royal Aeronautical Society

Professor Daping Chu
Fellow of the Institution of Engineering and Technology (IET)

Advisory Board Membership

Professor Paul Shore
Member of the Advisory Board of the RCUK Fusion Advisory Board

Professor Bill O'Neill
Member of the EPSRC Strategic Advisory Team

Editorial Boards

Professor Daping Chu
Founding Editor for Flexible and Printed Electronics, IOP Publishing (2014-)

Editor for Light: Science and Applications, Nature Publishing Group (2014-)

Industrial Appointments

Professor Paul Shore
Director of Loxham Precision Ltd

Paul Morantz
Director of Loxham Precision Ltd

Professor Daping Chu
Director of Roadmap Systems Ltd

Panel member: RBS Innovation Gateway (2014-2015)

Academic Appointments

Professor Daping Chu
Honorary Professor, Beijing Information Science and Technology University, China

Guest Professor, Southeast University, Nanjing, China

Distinguished Visiting Professor, Tsinghua University, China

Research Council Membership

Professor Paul Shore
Member of the EPSRC Peer Review College

Professor Daping Chu
Member of EPSRC Peer Review College

Learned Societies/Professional Bodies Membership

Professor Paul Shore
Past President of the European Society for Precision Engineering and Nanotechnology

Professor Bill O'Neill
Board of Directors, Laser Institute of America

Conference Programme Chairs/Committee Members

Professor Paul Shore
12th International Conference and Exhibition of the European Society for Precision Engineering and Nanotechnology, Stockholm, Sweden

13th International Conference and Exhibition of the European Society for Precision Engineering and Nanotechnology, Berlin, Germany

Professor Daping Chu
Member of Executive Committee and Chair of Displays and Imaging (DIS) Sub-Committee, International Electronic Device Meeting (IEDM 2014), San Francisco, USA

Member of Advisory Committee, International Conference on Electronics, Communication and Information Technology (ICECIT 2013), Patiala, India

Member of International Advisory Board, International Conference on Novel Non-volatile Inorganic Memory Devices: Materials, Concepts and Applications (in conjunction with CIMTEC 2014), Italy

Co-Chair of Symposium DD: Emerging Materials and Devices for Future Nonvolatile Memories, MRS 2013, San Francisco, USA

Member of Sensors, MEMS, BioMEMS, Displays and Imaging (SMBDIS) Sub-Committee, International Electronic Device Meeting (IEDM 2013), Washington DC, USA

Member of Technical Programme Committee, EuroDisplay 2013, London, UK

Member of Advisory Board, World Congress on Nano Sciences and Technologies 2012, Qingdao, China

Co-Chair of Organising Committee, ITC'11 - International Thin-Film Transistor Conference 2011, Cambridge, UK

Professor Bill O'Neill
Panel Chair, LAE Conference, Robinson College, Cambridge, UK.

Promotions

Professor Daping Chu
University of Cambridge, promoted to Professor

Dr Renaud Jourdain
Cranfield University, promoted to Lecturer

Dr Christopher Sansom
Cranfield University, promoted to Associate Professor

Professor Tim Wilkinson
University of Cambridge, promoted to Professor

Professor Bill O'Neill
University of Cambridge, promoted to Professor

Professor Paul Shore
Cranfield University, promoted to Head of Engineering at the National Physical Laboratory (retaining part-time role at Cranfield University)

Paul Morantz
Cranfield University, promoted to Director of the EPSRC Centre for Innovative Manufacturing in Ultra Precision

External Examiner Appointment

Dr Christopher Sansom
Appointed external examiner at the University of Manchester for PhD student Christos Kettinis: "Electrical supply and demand in Cyprus: Optimal use of renewable energy sources in electricity production"

Professor Daping Chu
External examiner for PhD degrees at Cranfield University, Heriot-Watt University, The University of Liverpool, University of Oxford, University of Warwick.

Professor Paul Shore
External examiner at KTH Stockholm, KU Leuven, TU Eindhoven, TU Delft, University of Manchester, University of Cambridge, University of Strathclyde, University of Huddersfield.

Panel member for the mid-term reviews of the EPSRC Centre for Innovative Manufacturing in Laser Based Production Processes led by Heriot Watt University and the EPSRC Centre for Innovative Manufacturing in Photonics led by the University of Southampton.

Awards and Prizes

Professor Paul Shore
NASA and ESA Significant Achievement Awards in recognition for "extraordinary contributions to the James Webb Space Telescope mission"

Dr Chris Williamson
Awarded Entrepreneur Fellowship from the Royal Academy of Engineering

Appendices

Steering Group

Academic and industrial steering group members throughout the duration of the programme:

Dr Paul Atherton (Chairman) Nanoventures

Dr Karen Brakspear EPSRC

Dr Tony Chapman EPSRC

Prof Daping Chu University of Cambridge

Gerard Davies EPSRC

Prof Chris Evans University of North Carolina at Charlotte

Chris Rider University of Cambridge

Prof Richard Hague University of Nottingham

Andrew Hurst Qioptiq

Christian Inglis Innovate UK

Dr Richard Langford University of Cambridge

Prof Richard Leach University of Nottingham (initially the National Physical Laboratory)

Dr Peter MacKay Gooch & Housego (UK) Ltd

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 (initially Cranfield University)

Dr Tom Taylor Centre for Process Innovation Ltd

Dr Ceri Williams University of Leeds

Prof Tim Wilkinson University of Cambridge

Dr Robin Wilson Innovate UK

Dr Andy Sellars Innovate UK

Industrial Supporters

3D Evolution

Aerotech

Agency for Science, Technology and Research, Singapore

Aixtron

Base4Innovation Ltd

Cambridge X-Ray Systems

Centre for Process Innovation

Cheyney Design & Development

Contour Fine Tooling Ltd

Fives Cinetic

HAMAMATSU Photonics UK Limited

Hitachi High-Technologies Europe GmbH

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 Limited

Qioptiq

Renishaw

Sphere Medical Limited

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 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

Science and Technology Facilities Council

Tianjin University of Science and Technology China

University of Hannover 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

Industrial Collaborators

ALE Ltd

Amplitude Systèmes France

Carl Zeiss Germany

Fanuc CNC UK Ltd

Gooch & Housego PLC

Heidenhain (GB) Ltd

Hexagon Manufacturing Intelligence

IPG Photonics

Jaguar Land Rover

Michell Instruments

M-Solv Ltd

Centre Management Team

Academic and industrial Centre management team members throughout the duration of the programme:

Dr Paul Comley Cranfield University

Prof Daping Chu University of Cambridge

Dr Richard Langford University of Cambridge

Prof Richard Leach University of Nottingham (initially the National Physical Laboratory)

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

Prof Paul Shore National Physical Laboratory (initially Cranfield University)

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

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 Completed 2016
Dulce Augilar-Garza	University of Cambridge	Design, Fabrication and Characterisation of Hierarchical Branching Vascular Networks	2014 (MRes) 2015 (PhD)
Peter Atkin	University of Cambridge	MRes in Ultra Precision Engineering	2016 (MRes)
Matt Bannister	University of Cambridge	The Interaction Between Ultrafast Lasers and FIB Machined Silicon for the Removal of Implanted Gallium	2012 Writing PhD thesis
James Barrington	Cranfield University	A Precision Fibre Optic CO_2 Sensor CO_2 Sensor	2015
Charlie Barty-King	University of Cambridge	MRes in Ultra Precision Engineering	2016 (MRes)
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)
Peter Christopher	University of Cambridge	MRes in Ultra Precision Engineering	2016 (MRes)
Clare Collins	University of Cambridge	Ordered Nanomaterials for Electron Field Emission	2013 (MRes) 2014 (PhD)
Jack Cook	University of Cambridge	MRes in Ultra Precision Engineering	2016 (MRes)
Lily Delimata	University of Cambridge	A method of consolidating powder layers in a single exposure using shaped intensity profiles of light	2015 (MRes) 2016 (PhD)
Ashley Dennis	Cranfield University	MRes in Ultra Precision Engineering	2016 (MRes)
Andrew Dickins	Cranfield University	MRes in Ultra Precision Engineering	2016 (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 Writing PhD thesis
Fabien Duarte Martinez	Cranfield University	MRes in Ultra Precision Engineering	2016 (MRes)
Wenhe Feng	University of Cambridge	Precision Glass Microstructuring Using Femtosecond Laser Induced Chemical Etching	2012 Completed 2016

Researcher Name	University	Project Title	Year Project Started
Will Fowler	University of Cambridge	MRes in Ultra Precision Engineering	2015 (MRes) Completed 2016
Nadeem Gabbani	University of Cambridge	Energy beam techniques and novel plasma diagnostics for the advancement of spacecraft propulsion	2015 (MRes) 2016 (PhD)
Daniel Gortat	University of Cambridge	Anode Materials for High Power Microwave Devices	2014 (MRes) 2015 (PhD)
Jiho Han	University of Cambridge	High Power Laser System with Built-in Dynamic Beam Shaping Capabilities	2012 (MRes) 2013 (PhD)
Aroop Kumar Sen	University of Cambridge	MRes in Ultra Precision Engineering	2016 (MRes)
Katjana Lange	University of Cambridge	Ultrafast Machining of High Temperature Superconductor Nanostructures for Novel Mesoscale Physics	2015 (MRes) 2016 (PhD)
Elkin Lopez-Fontal	University of Cambridge	MRes in Ultra Precision Engineering	2016 (MRes)
James Macdonald	University of Cambridge	MRes in Ultra Precision Engineering	2016 (MRes)
Aimal Mazidi	Cranfield University	MRes in Ultra Precision Engineering	2016 (MRes)
George Meakin	University of Cambridge	Display Motion Error Reduction through Novel Binary Dithering Schemes	2013 (MRes) 2014 (PhD)
Fanfan Meng	University of Cambridge	MRes in Ultra Precision Engineering	2016 (MRes)
Laurent Michaux	University of Cambridge	Control of Residual Stress and Failure Mechanisms for CS and LCS	2012 Writing PhD thesis
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) Writing PhD thesis
Jon Parkins	University of Cambridge	Novel Energy Delivery Techniques for Laser Additive Manufacturing from Metal Powders	2012 (MRes) 2013 (PhD) Writing PhD thesis
Andy Payne	University of Cambridge	Multiple-Beam Powder Bed Fusion Additive Manufacturing	2012 Writing PhD thesis
Ludmil Petkov	Cranfield University	MRes in Ultra Precision Engineering	2016 (MRes)
Matt Pryn	University of Cambridge	Jaguar Land Rover iHUD Project	2013 (MRes) 2014 (PhD)
Diego Punin	University of Cambridge	MRes in Ultra Precision Engineering	2014 (MRes)
James Ryley	University of Cambridge	Instrumentation of CNT nanowire production	2015 (MRes) 2016 (PhD)

Researcher Name	University	Project Title	Year Project Started
Jaliya Senanayake	University of Cambridge	Optimising the Performance of Fibre Optic Sensors using Holography	2012 Completed 2017
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 Completed 2016
Nan Yu	Cranfield University	Advancement of Plasma Figuring Technology to Reduce MSF Errors of Metre-Scale Optical Surfaces	2013 Completed 2016

Contact us

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EPSRC Centre for Doctoral Training in Ultra Precision

Centre for Industrial Photonics,
Institute for Manufacturing, University of Cambridge,
17 Charles Babbage Road, Cambridge,
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Contact: Mrs Sophie Fuller
Email: sg523@cam.ac.uk

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www.ultraprecision.org

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