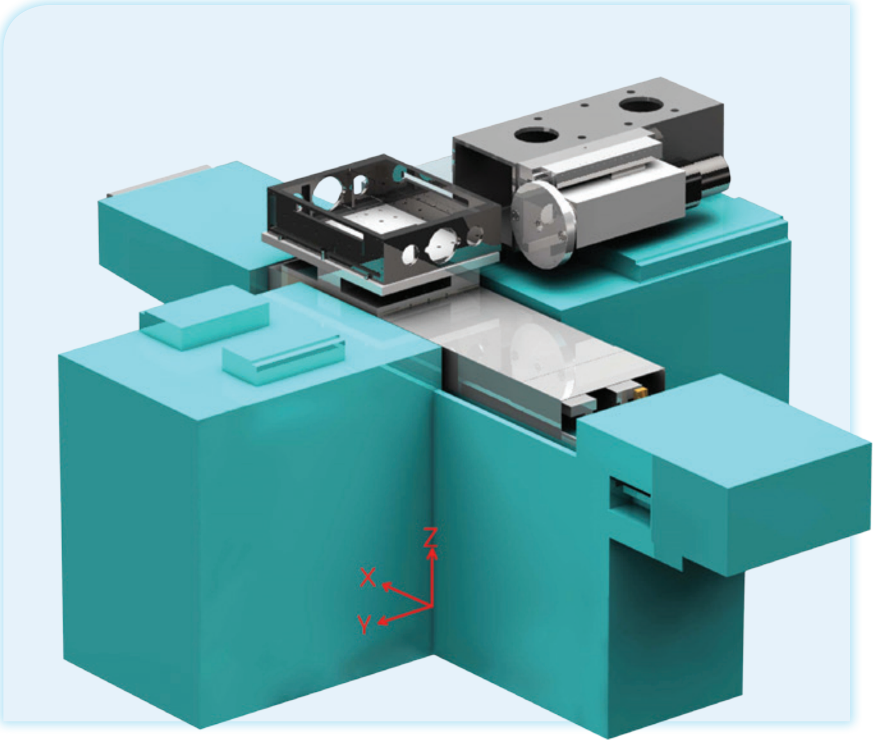
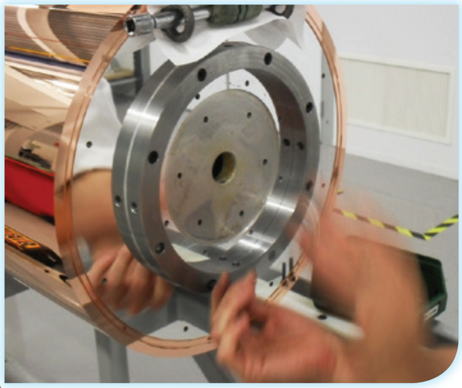
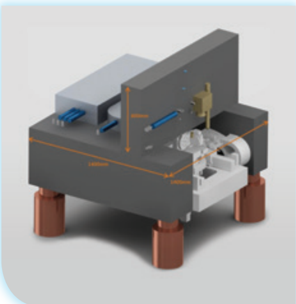
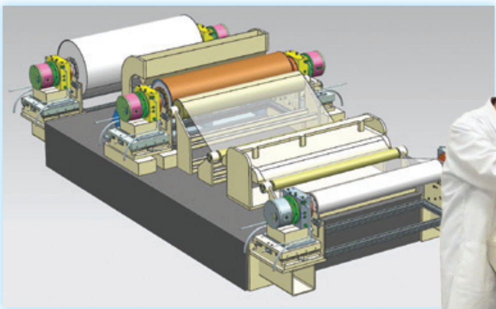
EPSRC Centre for innovative manufacturing in ultra precision

EPSRC
Pioneering research and skills





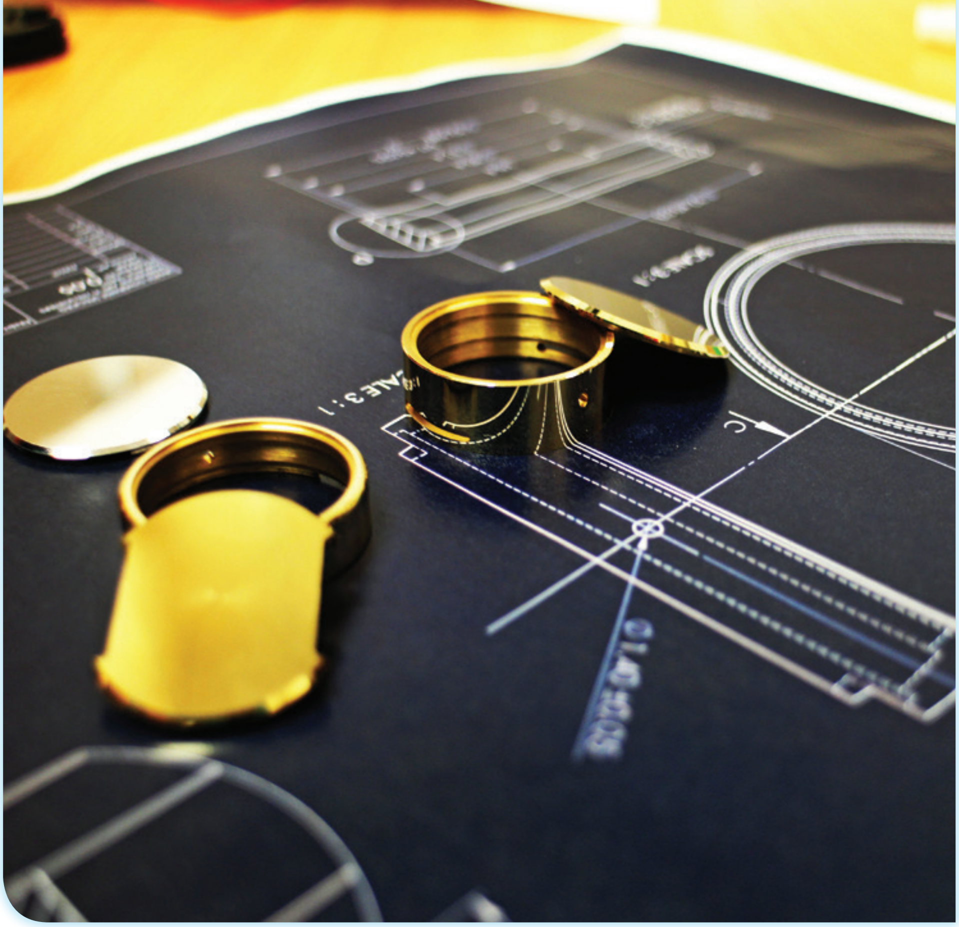




Mid-Term Report

May 2014

www.ultraprecision.org



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 and eu**spen** Ltd.

Executive Summary

At mid-term point the Engineering Physical Sciences Research Council (EPSRC) Centre for Innovative Manufacture in Ultra Precision has made significant progress in developing its three main activity arms. Together with its aligned Centre for Doctoral Training the overall the EPSRC Ultra Precision provision has already established itself as an internationally significant research and training centre.

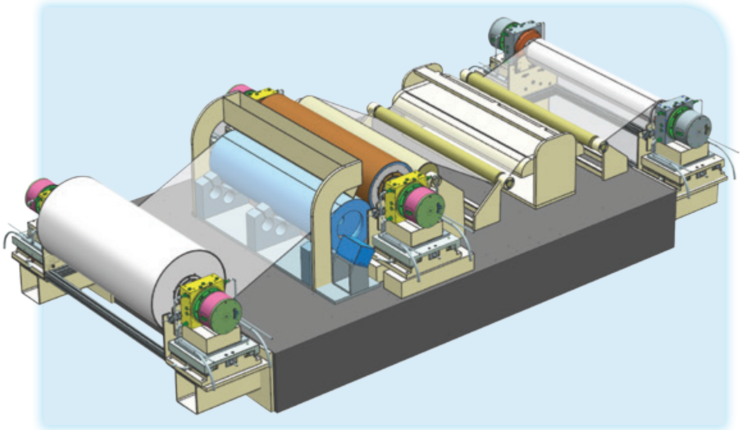
Our headline goal is to better position the UK to secure wealth creation from manufacturing products stemming from inventions in emerging markets. To achieve this goal we are advancing the UK capacity to perform early stage production research by establishing new processing technologies and machines demanded for effective production of emerging products. Our technical focus is firmly set on realising novel research platforms and processes that can define a new generation of rapid and effective ultra-precision production systems.

Our success will be measured by our ability to reconcile the simultaneous demands of:

- Nanometre scale/accuracy 3D feature creation
- Multi-material processing
- Rapid production capacity and
- Overall scale

In short, we aim to be able to produce nanometre scale features and effectively apply them precisely to large scale surfaces in order to realise new products.

This mid-term report provides insight of our progress against this technical ambition. We report significant achievement and increasing intensity in regards the creation of three unique Research Platforms that are being conceived, designed and developed by our researchers. These machines are being created whilst also developing a strong UK centred manufacturing supply chain that is sensibly supported by the World's leading international precision engineering companies. The Research Platforms programme has already secured over £1 million of additional investment. Our Research Portfolio provides the Centre with key process research advancement together with in-depth machine technology innovations. The portfolio already has 16 projects with over 20 external companies/organisations engaged.



Our National Strategy Programme has made significant steps forward. Its website and supporting information services are fully developed and are seeing notable usage with excellent basis for growth and influence. Progress in creating the UK Ultra Precision network has also been excellent having already run 6 national events around the UK attracting over 150 attendees. Our Educational Programme, themed around Watch IT Made™, has proved a fantastic success with enormous interest. Getting children enthused into Precision Engineering through them manufacturing their own high quality watches has proved a huge success: with the children and their parents. Its business concept of 'manufacturing within retail space' is based on providing a personal manufacturing experience and pride of creating an own-styled and branded quality UK produced engineering product. It is fair to report this combined business and educational concept has attracted significant attention of many individuals and organisations. It stimulates curiosity of producing.

At this mid-term point we have made very good progress with all aspects of the Centre. Our foundations are well established with a good level of intensity build up. During the second half of the centre's 5 year funding we will plan for a broadening of industrial engagement, cementing of our research outputs and operational capability. The success in securing long term funding for our aligned Centre for Doctoral Training has provided a much welcomed longer duration supply of aspiring precision engineers and scientists.

We believe that we are well placed to become the World leading ultra precision research centre, we have good UK and International engagement and nicely developed long term mechanisms to broaden our influence.

This mid-term report should be read in conjunction with the recently submitted second annual report to gain a wider appreciation of our work, its challenges and perhaps most importantly our speed of progress.

Paul Shore
Centre Director

National Strategy Programme Development

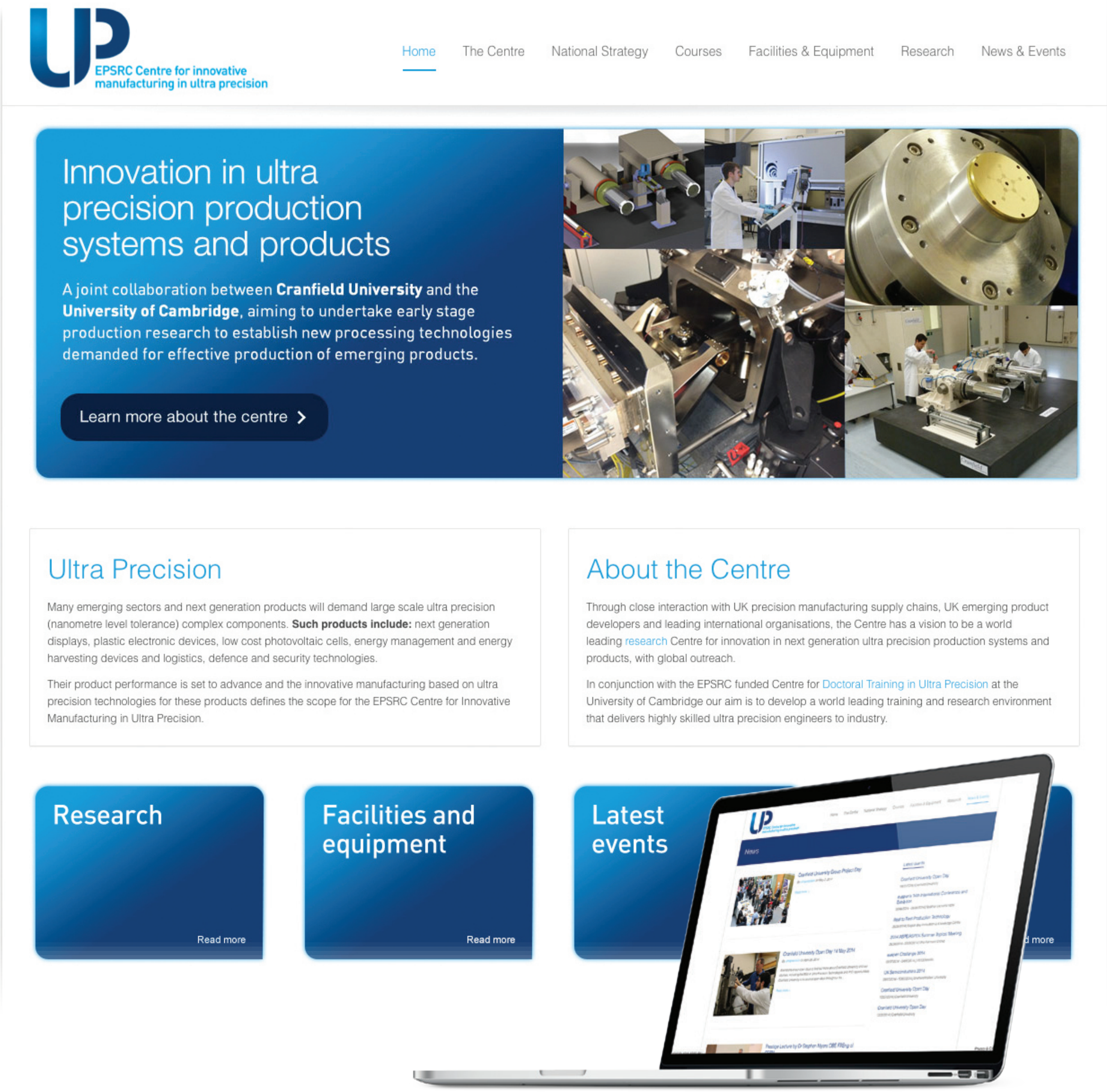
National Strategy Programme for Ultra Precision

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

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

The key elements of the National Strategy Programme include:

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

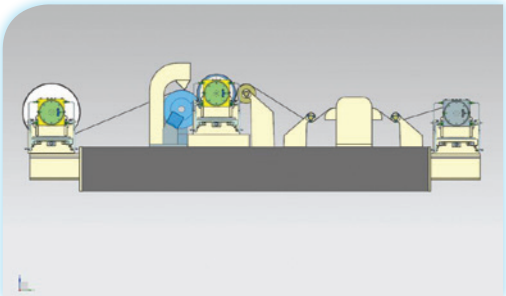


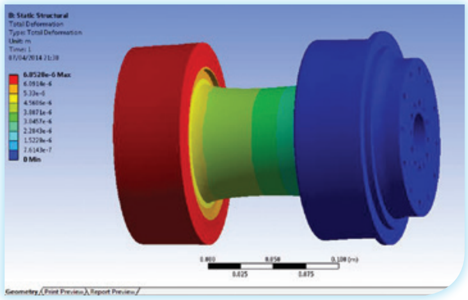
Ultra Precision Website and UK Database of Ultra Precision Facilities

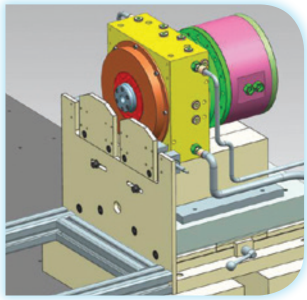
The Centre's website ultraprecision.org was launched in May 2013 and is the Centre's primary resource for informing the ultra precision community and the general public about its complete spectrum of research activities, the National Strategy Programme, UK ultra precision database of facilities and equipment, news and events, linking into the Centre for Doctoral Training in Ultra Precision led by the University of Cambridge.

In addition to its own activities, the website advertises worldwide ultra precision events including those of the European Society for Precision Engineering and Nanotechnology (euspen) and the American Society for Precision Engineering (ASPE). Events associated with other EPSRC Centres for Innovative Manufacturing of relevance are also listed as are events where the Centre plans to exhibit or where Centre staff will be presenting research papers

Since the second annual report published in November 2013, the website has developed further and now encompasses the National Strategy Programme, which provides the public with full details of its outreach activities. The Centre's outreach activities are depicted as a series of portfolios linking into industrial and academic based activities. This new area of the site also includes an 'ultra precision community' page which lists industrial companies and universities in the ultra precision engineering community. Some of the companies and universities listed are existing industrial supporters of the Centre and establishments that have contributed to our outreach events either as invited speakers or registered delegates. The aim of this community page is to establish a UK supply chain and database of businesses with the expectation that the relationships between the Centre and those listed will develop further in the future e.g. sponsored research projects or joint research collaborations aiding translation to wealth.







The method in which the Centre's research is depicted on the website has also evolved. The Centre's Research Portfolio shows the projects that the Centre's students are engaged in, which link directly to the Research Platforms part of the website. The Research Portfolio is displayed in a user friendly way so visitors can see which research projects are directly linked to which platform. The portfolio is updated as student projects progress, ensuring the site is kept as current as possible. A new area where users may download research outputs has also been added to the main Research part of the website. Downloadable outputs include journal and conference publications, reports and outreach presentations. Contributions to this area of the site come from staff within the Centre management team.

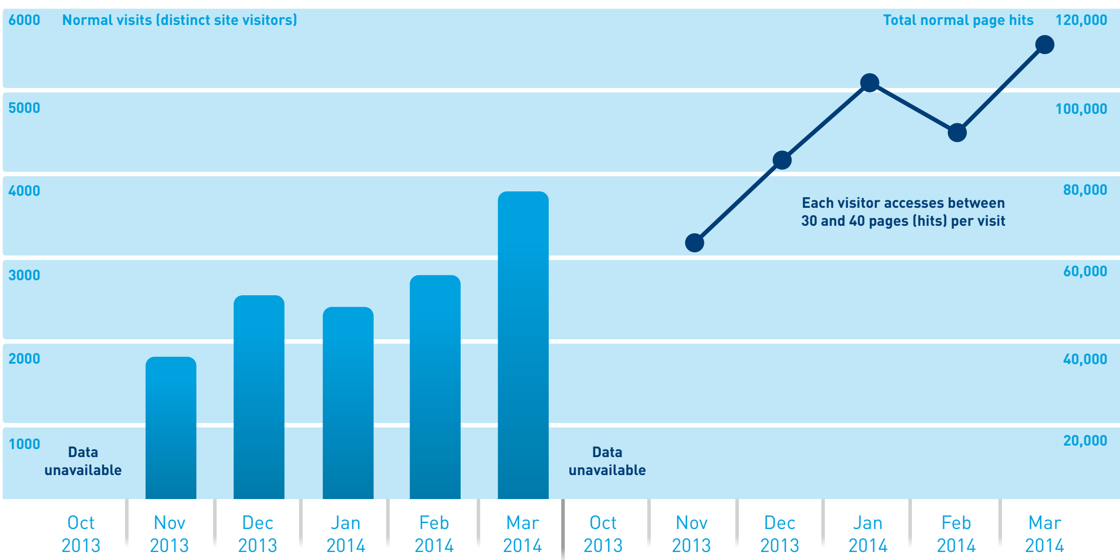
Additional details about the Precision Engineering Institute at Cranfield and the Institute for Manufacturing at Cambridge have been incorporated into the website to give users further knowledge about the two institutions that manage the Centre. The 'People' section of the website has been visually improved to include photographs and a more streamlined method of finding out more about the team behind the Centre.

The News and Events section of the site has been streamlined into one menu option and the events area of the site has been updated so that users wishing to attend Centre led events can now register online.

The web service is a dynamic aspect of the Centre's activities and it is expected additional content will be developed as the National Strategy Programme progresses. Monthly web traffic has doubled over the past 5 months from just below 1750 in October 2013 to 3800 in March 2014 (excluding all robot searches and static data accesses). Each distinct visitor accesses between 30 and 40 web pages per month. Although some are repeated visits to the same pages it is proving that visitors are returning back to access content regularly. The events and facilities pages are the most visited sections, followed by the home page. The majority referral (nearly 80%) is from e-mail rather than search engines or other websites, suggesting targeted contacts are providing more traffic than internet searches of our keyword content.

The UK database of ultra precision facilities and equipment is openly available with detailed and up-to-date information on the UK's leading ultra precision laboratories and the equipment housed. Utilisation levels of the equipment are listed and access availability for commercial and research opportunities indicated. Since November 2013, the listings on the database have steadily increased from 41 to 74. The database is also linked to the EPSRC website detailing broader equipment resources.

Webstats

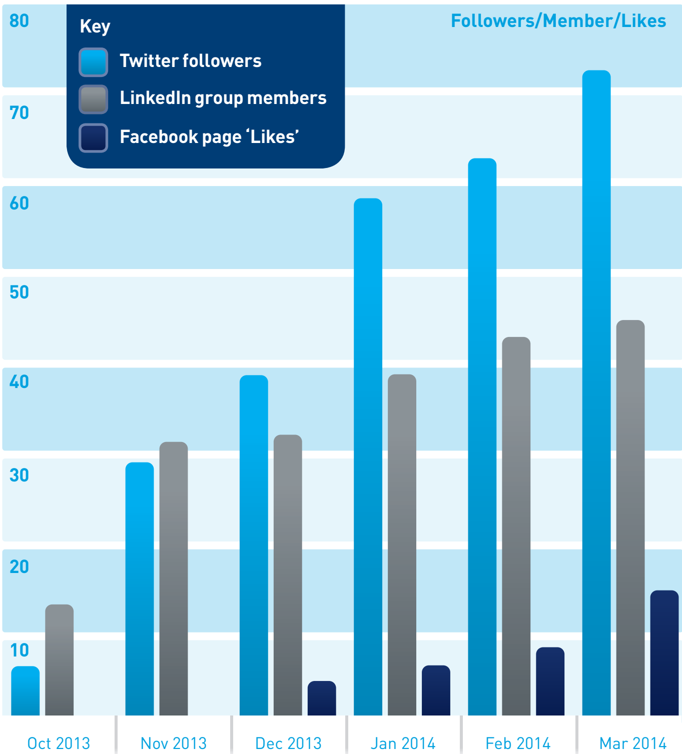


Note: excludes robot searches, static data.

Social Media Engagement

Social media has only been running since late 2013. The media is used to provide news items of interest to the community and to provide updates on events that are upcoming. The primary portal for direct engagement from the community remains the website and most social media activities direct interested parties to the website.

Twitter **(@UPrecisionUK)** has been the largest growing area of engagement via social media, followed by LinkedIn **(Ultra Precision UK Network Group)** and lastly Facebook **(Ultra Precision UK)**. In general these media streams are used in distinct manners; Twitter provides event information and some generic news items from retweets of interest to the ultra precision business and academic community. LinkedIn is primarily a business tool and as well as the Centre's own event activities, links are occasionally provided to business articles that may interest the community, but little direct academic content. Facebook is primarily aimed at students and researchers in the ultra precision field, while again this links events from the Centre, its primary purpose is to try and increase educational and academic outreach.



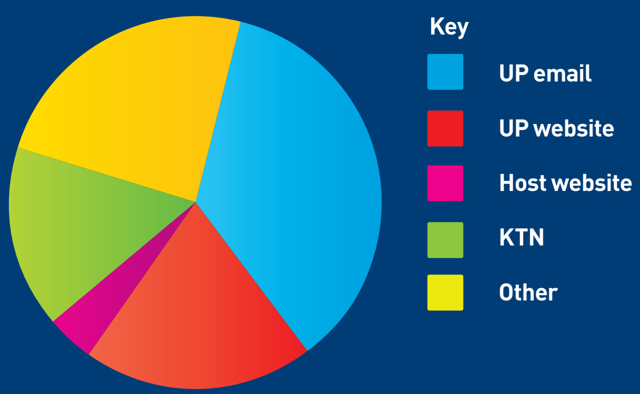
Social Media Development

Centre Outreach Event Feedback Analysis

At each event the Centre has requested feedback from delegates so that it can track issues that are popular, or not, with the ultra precision community that are actively engaging with the Centre. Current analysis suggests the Centre has hit a relatively successful formula of a mix of seminars, site visits (facilities tours) and locations around the UK; we go to the community rather than expecting them to come to us.

Mean delegate responses are all above the "met expectation" level of 3, most above the "exceeded expectation" level.

To ensure the Centre is aligning its dissemination strategy for events with the website and social media presence, we also collect information on where delegates found out about the events. Most attendees are getting their information via e-mail, hence have become registered with the Centre (or via a colleague who has registered). The website is also proving itself as the primary communication channel and bringing in a large proportion of delegates; this aligns with the web statistic data on site traffic being dominated by e-mail referrals.



Engagement Channel Analysis for Networking Events

The business that each delegate is employed by is also monitored and to date these events have attracted over 40 different businesses, of which 28 had not engaged previously with the Centre. This is proving the effectiveness of the outreach and networking events.

Outreach

November 2013

Metrology Technologies to Enable Reel to Reel Processing of Emerging Products

National Physical Laboratory, Teddington, UK.

A successful metrology themed meeting was held at the National Physical Laboratory. The meeting attracted 40 attendees from academia and industry with research interests in metrology needs to support future reel to reel processing technologies. The day included presentations and laboratory tours of the National Physical Laboratory's facilities.

January 2014

EPSRC Centre in Medical Devices Launch

Metropole Hotel, Leeds, UK.

The Centre exhibited at the launch of the EPSRC Centre in Medical Devices, providing both literature and physical examples. The samples demonstrated how ultra precision manufacture can be used to create low cost microfluidic components for species separation and prototype examples of small articulated joints in stainless steel, manufactured using a novel 3 stage microinjection moulding process that produces no residual stress in the material.

Cambridge Science Festival

University of Cambridge, UK.

Each year the Institute for Manufacturing welcomes over 1000 visitors to its Manufacturing Zone, as part of the annual Cambridge Science Festival with a host of displays, exhibitions and hands on activities that are designed to educate and inform people of all ages of the science and technology of manufacturing. This year the Centre provided a range of new exhibits and activities. The MRes students from Cambridge offered children the chance to personalise their own watch strap designs using laser marking technology. Other activities included demonstrations of ultra high precision machining of magnesium with our ultra-fast lasers, laser graffiti writing using fingertip control of blue lasers energizing photo-luminescent wall paper and exhibitions of ultra precision motion control from one of our industrial collaborators, Aerotech UK Ltd.

External events – the Centre attended since October 2013

Our own events

February 2014

Photonics West 2014

San Francisco, USA.

The Centre joined the the EPSRC Centre in Photonics and the EPSRC Centre for III-V Technologies at this conference to exhibit as part of a UK cluster stand. This large event provided wide ranging international exposure for UK ultra precision technologies and research. In particular the imprinting of nanoscale optical features from Cranfield's UPS² facility in Wales was exhibited alongside the wider range of free-form surface structuring capabilities of UPS² and the Precision Engineering Institute at Cranfield University.

February 2014

Plastic Electronics Fabrication Technologies

Centre for Process and Innovation, Sedgefield, UK.

The Centre held its first outreach meeting of 2014 at the Centre for Process Innovation, Sedgefield, part of the TSB High Value Manufacturing Catapult. The meeting was a great success with 40 delegates in attendance from across academia and industry discussing plastic electronic fabrication technologies research and production, including its application in end products. The day included a tour of the process facilities at CPI, a corridor tour of their cleanrooms and a close-up guide to their roll-to-roll machine.

March 2014

April 2014

MACH 2014

NEC, Birmingham, UK.

The Centre had a stand as part of Cranfield University's presence at the exhibition. MACH is the UK's leading machine tool exhibition; hence the focus for the Centre was the meso scale research platform and larger precision diamond turning capability. It was also a chance to connect with many of the precision engineering community who are on the cusp of ultra precision work and to reach out to help those businesses make the transition from precision to ultra-precision.

April 2014

Future Display Technologies and Production Demand

University of Cambridge, UK.

The Centre's second outreach event of the year was hosted by the Centre for Advanced Photonics and Electronics (CAPE) at Cambridge. The day included talks from industry including Jaguar Land Rover, Novalia, Smithers and 3M. The event gave researchers and industrial developers the opportunity to exchange ideas and find out what is the current state-of-the-art in the emerging area of display technology. 76 people attended the event.

April 2014

Prestige Lecture by Dr Stephen Myers OBE FREng of CERN

Cranfield University, UK.

The Centre hosted a Prestige Lecture by Dr Stephen Myers OBE FREng, Head of Medical Applications and former Director of Accelerators and Technology at CERN (European Organisation for Nuclear Research) entitled 'The Engineering Needs for Particle Physics and the CERN Large Hadron Collider (LHC)'. The lecture provided the audience with an overview of some of the engineering requirements for construction and operation of modern day accelerators with particular reference to the LHC. A short description of the steps to increase the performance of the LHC which allowed sufficient data to be accumulated for the discovery of the Higg's boson was also given. Details of the medical applications resulting from the CERN engineering technologies was also included. Steve, who hails from Belfast was introduced by Sir Peter Gregson, Cranfield University's Vice Chancellor. CERN are sponsoring 2 PhD students at Cranfield to support their metrology needs for the LHC replacement.

April 2014

Visit of NSK Ltd

Cranfield University, UK.

The Centre hosted a two day visit at Cranfield from alumni Dr Satoru Arai of NSK Ltd, Japan in April 2014. NSK is one of the world's leading manufacturers of rolling bearings, automotive products, precision machinery and mechatronics products. Dr Arai undertook his PhD at Cranfield's Precision Engineering Institute and was accompanied by his colleague Mr Takashi Yoshimura, who will be deployed by NSK later this year to undertake his research degree within the Precision Engineering Institute. Guests from NSK's UK and German office were also present and were provided with an insight of the research work being undertaken within the Centre. NSK have now agreed to send Mr Yoshimura to undertake research with the Centre for a minimum of 2 years.

Educational Outreach

September 2013

Precision Engineering Short Course Cohort with Prof Martin Culpepper of MIT (back row, right) and Prof Paul Shore (front row, right).

Precision Engineering Industrial Short Course

Cranfield University, UK.

The Centre delivered a Precision Engineering Industrial Short Course in September 2013. This was five day intensive short course covering the basic principles and state-of-the-art concepts to increase the precision, accuracy and reliability of machine tools and products. Delegates that attended were from AWE, Cranfield Precision, Diamond Light, European Southern Observatory and FANUC. Guest lecturers were Prof Martin Culpepper of the Massachusetts Institute of Technology (MIT), USA, Prof. ir. Robert Munnig Schmidt of Delft University of Technology, Denmark and Richard May-Miller of Cranfield Precision.

February 2014

Work Experience Placement

Cranfield University, UK.

A student from the Sir Henry Floyd Grammar School in Aylesbury studying A-levels spent a week at Cranfield in February undertaking work experience. Activities she undertook included operating and programming of a Kern micro milling machine, diamond turning, how to read detailed drawings (geometric tolerance and dimensioning), operating co-ordinate measuring machines and writing simple metrology programs for different components, with both tactile capability and vision system. The MRes group project students based at Cambridge also spent some time with her working on the Watch it Made™ educational demonstrator programme. Activities included watch component assembly and CAD programming.

Work experience student with our Precision Engineering Institute technicians and Dr Paul Comley (right).

April 2014

Watch It Made™ Engages Fulbrook Lower School Pupils

Cranfield University, UK.

As part of the Cranfield group project Watch It Made™, the Centre welcomed a group of 12 year old children from Fulbrook Middle School, Woburn Sands. The children made two visits. During the first visit the pupils told of what they liked about watch designs. Subsequently, they were sent by email a "watch design selector" form. Using this selector form they created their own watch designs. On their second visit to Cranfield they made their own designed watch. The Cranfield students measured the emotions of the children before and after they made their own watches to insight about their "proudness in producing". The children all seemed very pleased with their watches.

May 2014

euspen Challenge National Heat, UK

Hexagon Metrology, Milton Keynes, UK.

The eu**spen** Challenge 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 current and 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 leading companies in the field.

The UK National Heats took place at Hexagon Metrology Ltd in Milton Keynes, UK and international students from the Centre entered as teams, representing Cranfield and Cambridge Universities. Research students Jonathan Abir and Nan Yu from Cranfield were successful in winning the UK National heat and will represent the Centre and Cranfield University at the eu**spen** Challenge at HEIDENHAIN GmbH, Traunreut, Germany in July 2014.

May 2014

Ultra Precision Research Student Conference

Cranfield University, UK.

The Centre organised this one day conference to bring together students working on research in the UK in the field of ultra precision engineering. The conference aim was to disseminate the activities in the UK research community and to assist researchers to get a broader understanding of what other activities are ongoing, and where possible collaboration or cross-fertilisation of research could be realised. Other EPSRC Centres for Innovative Manufacturing were invited to present. Overall presentations were given by students from Cambridge, Cranfield and the EPSRC Centre in Photonics, led by the University of Southampton. The European Society for Precision Engineering and Nanotechnology (eu**spen**) also presented an overview of its activities.

Further Outreach Activities

The Centre's National Strategy Manger, Martin O'Hara has been active in attending various one day events which include the **NMI Industry Summit** (Mayfair, London), **UK Inertial Fusion Network Kick-Off Meeting** (The Royal Society, London), launch of the **EPSRC Centre for Innovative Manufacturing in Medical Devices** (Leeds), **Hexagon Metrology Precision Centre Opening Event – Measurement Technology Workshops** (Milton Keynes), **Leading the Move from Diagnostics to BiognostiX** (Hauser Forum, Cambridge), **Photonics North West/Wales Seminar & Manufacturing Electronic Systems of the Future** (Daresbury), **Manufacturing for Plastic Electronics Conference** (Clare College, Cambridge), **Photonex 2013** (Coventry), **Advanced Engineering UK** (Birmingham), **Precisiebeurs 2013** (The Netherlands) and **UK Plastic Electronics Research Conference** (Loughborough University).

Martin has also hosted and visited industrial companies with the aim of forging collaborations, student sponsorships and participation at the Centre's outreach events. Meetings with industry included **UK Manufacturing Accelerator** (Manchester), **Cranfield Precision** (Bedford), **Carbonlite Converting Equipment** (Rochdale), **Timsons** (Northamptonshire), **M-Solv** (Oxfordshire), **Bosch Rexroth** (Cambridgeshire), **Hone-All Precision** (Bedfordshire) and **Elektron Technology** (Cambridge).

A visit to the Centre for Process Innovation Limited in Sedgefield led to the company hosting the Centre's first outreach event of 2014 *'Plastic Electronics Fabrication Technologies'* in February.

Following the exhibition at **Photonics West 2014**, Martin visited the **National Ignition Facility (NIF)** at the **Lawrence Livermore National Laboratory** (CA, USA). The visit included a tour of the facility and discussions for further optical related research collaboration.

Martin O'Hara visiting the National Ignition Facility (NIF), Lawrence Livermore National Laboratory.

There was further collaboration with existing academic institutions including the **National Physical Laboratory** in Teddington who hosted the Centre's 'Metrology Technologies to Enable Reel-to-Reel Processing of Emerging Products' outreach meeting in November 2013. The **Centre for Advanced Photonics and Electronics (CAPE)** in Cambridge, co-sponsored the Centre's second outreach event 'Future Display Technologies and Production Demand' in April 2014 and in November 2014 the Centre will be holding its 'Micro Surface Structuring' meeting at **OpTIC Glyndŵr** in St Asaph, Wales. A visit was made to the **SPECIFIC Innovation & Knowledge Centre**, in Port Talbot where the Centre will be holding its 'Reel-to-Reel Production Technology' one day meeting in June 2014. **SPECIFIC** is an academic and industrial consortium led by **Swansea University** and **Tata Steel**.

The EPSRC Centre in Ultra Precision has forged relationships with other **EPSRC Centres for Innovative Manufacturing** including **Photonics, Advanced Metrology** and **Large Area Electronics**. Members of the **EPSRC Centres in Advanced Metrology** and **Large Area Electronics** have provided presentations at outreach events organised by the Centre in Ultra Precision. UK Universities have also linked into the Centre by providing presentations and general attendance at its own outreach events. These include the **University of Huddersfield**, **Brunel University**, **Imperial College London**, **University of Exeter** and the **University of Bath**.

The Institute for Manufacturing contributed with the hosting of a workshop 'Power Beam Delivery and Manipulation' organised by the Association of Laser Users which took place at the Hauser Forum, University of Cambridge in December 2013. The Centre for Industrial Photonics, led by Prof O'Neill provided delegates with a tour of its facilities.

Cranfield University's **Global CSP Laboratory**, '**The UK Centre for Concentrating Solar Thermal Manufacturing**' was officially launched on 26 March 2014. The Laboratory, located in the Precision Engineering Institute and led by Dr Chris Sansom, is the home of an internationally recognised research and manufacturing team working on concentrating solar power (CSP) and solar thermal (ST) technologies and their applications. The team is the largest CSP research activity in the UK and the only UK representative on the EERA (European Energy Research Alliance) Joint Committee on CSP. The Laboratory is sponsored by the UK company Global CSP who develop, design and manufacture components and systems for concentrating solar power applications worldwide.

Presentations

A series of presentations, including keynotes were presented at various conferences by Centre staff:

Prof Bill O'Neill, *"Advances in laser manufacturing"*
Institution of Mechanical Engineering, Institute for Manufacturing, March 2014, Cambridge, UK.

Prof Bill O'Neill, *"Ultra precision technologies"*
IfM, Manufacturing Review, Jan 2014, Cambridge, UK.

Prof Bill O'Neill, *"Innovation in Materials: Additive Manufacturing"*
Royal Academy of Engineering, November 2013, London, UK.
Watch on YouTube: www.youtube.com/watch?v=lzwMmL6lDYM

Prof Bill O'Neill, *"Preparing for the future at the IfM"*
International Laser Application Forum, April 2013, Nottingham, UK.

Prof Bill O'Neill, *"Supersonic laser deposition of metals"*
Manufacturing the Future, Sept 2012, Loughborough, UK.

Prof Daping Chu, *"Printed electronics – how to make transistors and displays from liquid source materials"*
(Invited talk), 4th Printed Electronics China 2013 (PE China 2013), September 2013m Suzhou, China.

Prof Daping Chu, *"High brightness reflective display to light and radiation control of green buildings"*
(Invited talk), EuroDisplay 2013, September 2013, London, UK.

Prof Daping Chu, *"Novel siloxane based smectic A liquid crystal materials: formulation, structures and optical device applications"*
(Invited talk), Organic Photonics and Electronics - Liquid Crystal XVII, August 2013, San Diego, USA.

Prof Daping Chu, "Laminated electro-active foils for the built environment"
(Invited talk), Large Area Electronics: Addressing the Applications Challenge, December 2012, Cambridge, UK.

Prof Daping Chu, *"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.

Launch of Global CSP Laboratory, March 2014.

Prof Daping Chu, *"Novel materials for light and radiation control of green buildings"*
(Plenary Lecture), The Second International Materials Forum (IMF2012), April 2012, Wuhan, China.

Keynote lectures

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

Prof Richard Leach, *"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.

Prof Richard Leach, *"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.

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

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

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

Prof Paul Shore, *"Thermal issues, past and present"*
euspen Special Interest Group: Thermal Issues, 19-20 March 2014, Zurich, Switzerland.

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

Future Outreach Events

The Centre will be exhibiting at the **National Manufacturing Debate** in May 2014 which is an annual event hosted by Cranfield University. The event brings together manufacturing professionals from a range of sectors to discuss and debate current challenges in the industry, and encourage networking and collaboration across the sector to enable continued and long-term growth.

In June 2014 the Centre will be exhibiting at the **euspen 14th International Conference and Exhibition**, Dubrovnik, Croatia. This conference offers the possibility to see that latest advances in traditional precision engineering fields such as metrology, ultra precision machines, ultra precision manufacturing, assembly processes, and motion control in precision systems.

Centre outreach meetings planned for the rest of 2014 include **Reel to Reel Production Technology** in June at the SPECIFIC IKC, Port Talbot and **Micro Surface Structuring** at OpTIC Glyndwr in November. The Centre is also planning to deliver the **Precision Engineering Industrial Short Course** again in September 2014.

Other conferences the Centre will be attending include the **3rd EPSRC Manufacturing the Future Conference** at Strathclyde University, Glasgow in September and **Advanced Engineering UK** at Birmingham in November. A more active participation is planned for **Precisiebeurs 2014** in December with the expectation of exhibiting at the event as part of a UK cluster-stand.

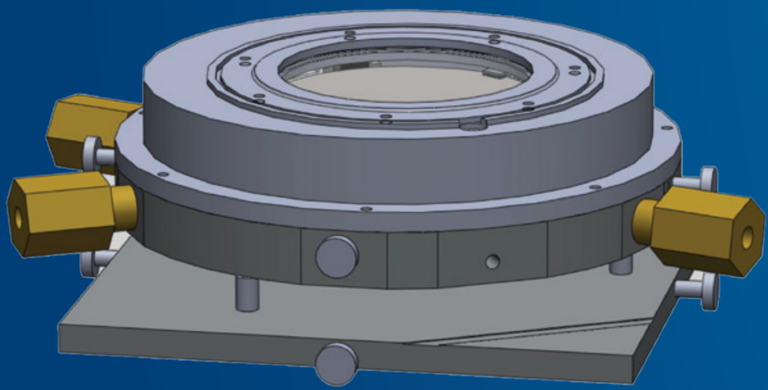
Educational Demonstrator Programme

As part of our National Strategy Programme the Centre committed to develop a number of educational demonstrators that would help raise public awareness and interest of precision engineering. After significant discussions between Paul Comely and Paul Shore, the 'Watch It Made™' concept was established. It is the mechanism to deliver the Centre's Educational Demonstrator Programme.

Watch IT Made™ is about enthusing young people into aspects of precision engineering by enabling them to produce their own high quality watch. Young learners design and make the significant watch components themselves; then they assemble their watch. This learning experience aims to give young people "pride of producing" a quality product. Activities have been developed to enable 12 year olds to accomplish the necessary tasks, i.ê. prior to their GCSE selections.

The UK has ~ 650,000 12 year olds in schools each year. The Watch It Made™ programme aims to create an opportunity such that all could make their own watches. The delivery mechanism will be by opening retail shops as opposed to offering this experience through schools. The Watch It Made™ programme has been advanced through group project studies at both Cambridge and Cranfield under the supervision of Dr Paul Comley and Professor Paul Shore.

Research Platforms



Batch processing and sample chamber

Nano-FIB Platform

A Nano Focused Ion Beam (FIB) platform is being developed to provide an ultra precision production platform capable of offering micro and nano-patterning of substrates with in-built metrology capabilities for a wide range of materials utilising an integration of laser, reactive atom plasma and focused ion beam technologies. The design brief requires length scale processing resolutions for the two principle processing routes; 30nm for the FIB and 200nm for the laser.

The past two years have seen a number of scoping studies aimed at testing the various integration strategies of laser/ion beam concepts. In addition to this, the programme has been exploring the processing capabilities of the latest He+ and Ne+ ion beam systems. It is clear from the early studies that an integrated laser/ion beam system would not deliver best performance, since the combined technology platform would not provide high levels of operational efficiency, and the use of larger scale laser based ablation processes within the ion beam chamber would be deleterious to the sensitive instrumentation within it.

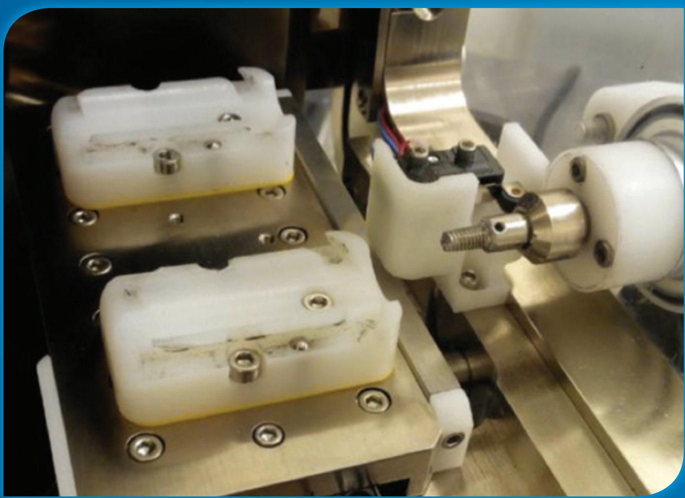
The laser processing studies have concentrated on investigating and specifying the basic laser system components and processing capabilities of a number of laser source technologies. Following this series of performance trials, the following laser technologies have been selected for integration in the Nano-FIB platform:

- Satsuma ultra fast laser (Amplitude Systèmes, France) - 10 W 500kHz @ 300 fs pulse width
- Talisker HE (Coherent Lasers, UK) - a multi-wavelength system operating at 1064 (20W), 532 (10 W), and 355nm (5 W) wavelengths, 1 MHz @ < 10 ps pulse width.

These systems were found to offer substantial processing capability 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.

The FIB machining studies have concentrated on exploring the potential of using a new He/Ne ion technology that has been developed by Carl Zeiss, one of the Centre's industrial collaborators. Traditional FIB nano machining capabilities have used Ga ions as the source technology, although it is well known the Ga machining results in significant Ga impregnation and a reduction of the material properties of the subject material.

Ultra precision process research, as described above, is investigating Ga removal techniques to mitigate the risk of Ga contamination. The use of Ne ions will offer increased resolution of 3nm rather than 30nm for Ga and a substantial reduction of ion implantation.

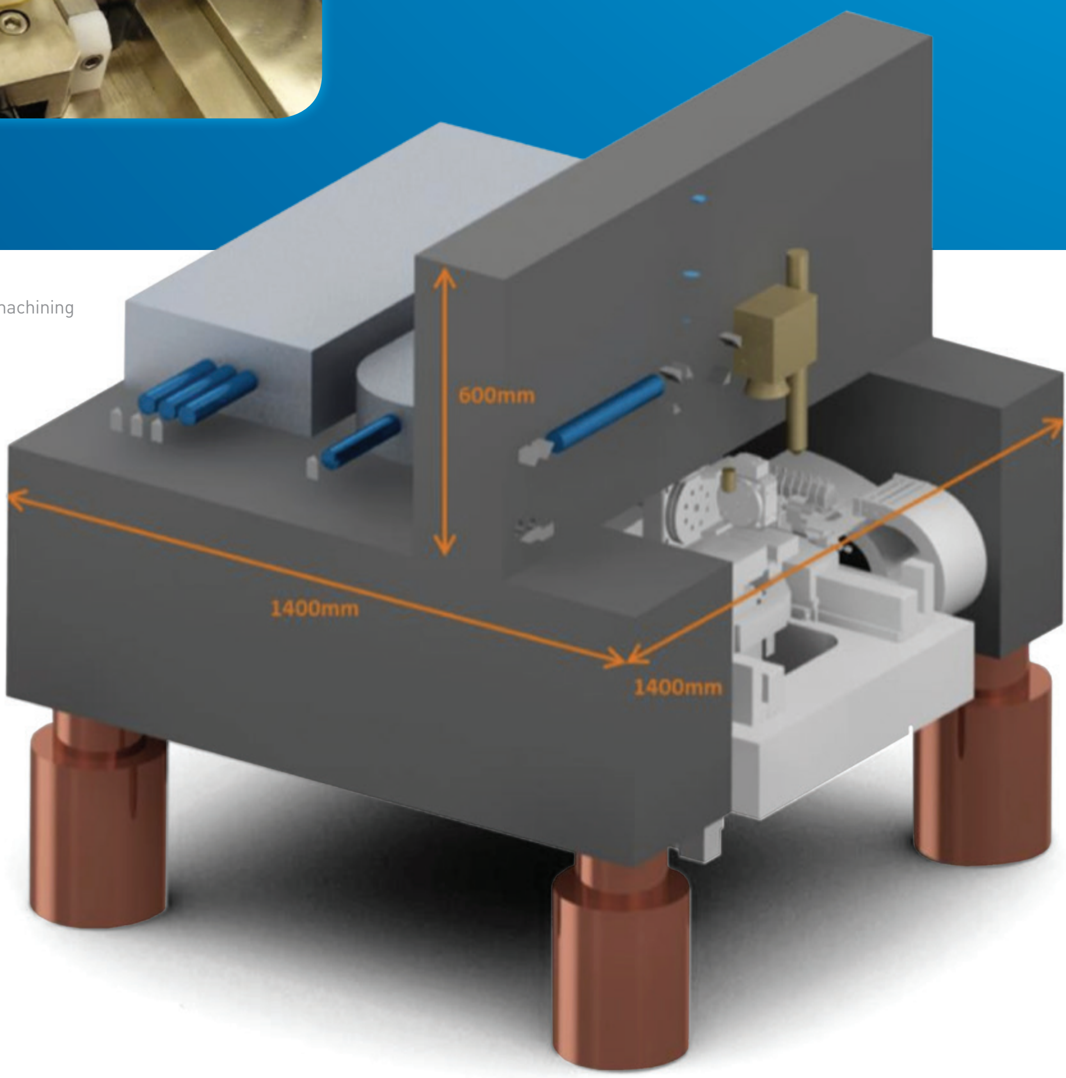


FIB sample mounting rig

Dr Richard Langford of the Cavendish Laboratory has explored capabilities of the new Ne ion systems with the support of Carl Zeiss researchers in Boston, USA. The conclusion is that the FIB platform should offer Ne ion machining capabilities and thereby give the new Nano FIB platform a world leading technology position on device resolution and performance, although the extra funding to acquire the new ion source technology is yet to be secured. Until new funding is acquired to enhance the FIB system with a He and Ne ion capability, the Nano FIB platform will continue as originally planned, and will be developed around a Ga+ ion beam system, namely the Zeiss Cross-beam technology.

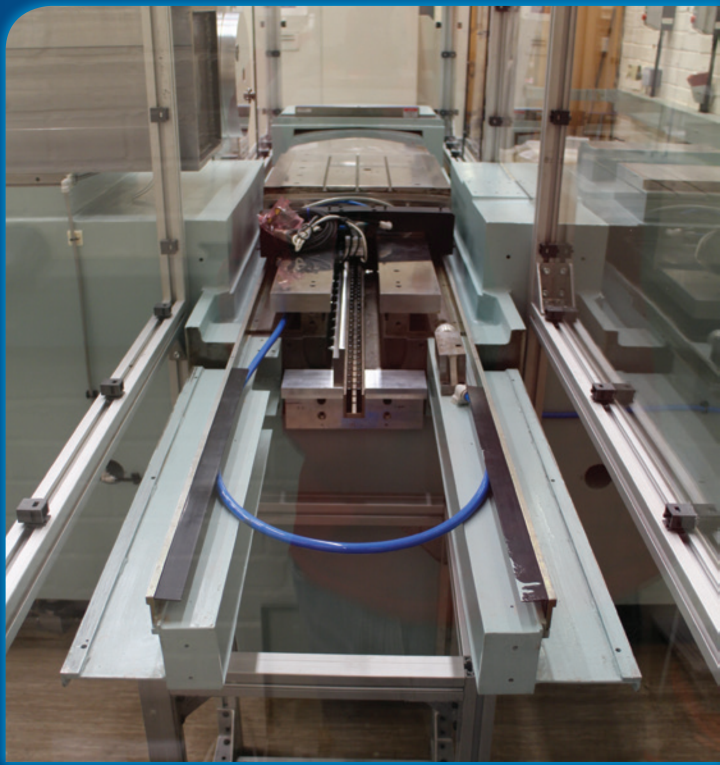
Design studies have been completed, which have established the specifications of the integrated process technology to include rapid laser machining sequences followed by FIB machining for high resolution part features. The metrology systems, namely an in-line optical coherence tomography system (point depth measurement), and a triple wavelength holographic microscope (2D topography) are currently in development in the research portfolio programme. These technologies will be incorporated into a Nano FIB process chain, comprising of a palletised sample processing chamber which will allow processing of 2 inch wafers under controlled atmospheres either by laser and/or FIB according to the needs of the device manufacture. The high precision laser workstation incorporating in-process metrology and FIB processing sequence is scheduled for completion in October 2014.

Precision machining station



Meso Platform

Meso platform and related technologies are being created to advance the µ4 concept towards a range of machine solutions. µ4 is a radical machine tool concept in which all systems of the machine are highly integrated and made small.



The most obvious benefit from this approach is that the machine is small. Other benefits include low energy requirements, improved dynamic performance, higher productivity, lower cost, ease of transport, reduced cost of ownership and eased automation potential.

Meso is defined to be able to process component parts of up to 100mm with sub 100 nm feature sizes and form accuracy tolerances. Meso research aims at enabling leading processing capabilities covering diamond machining, imprinting, plasma and laser processing and automated operation.

µ4 Diamond Machining Evaluations

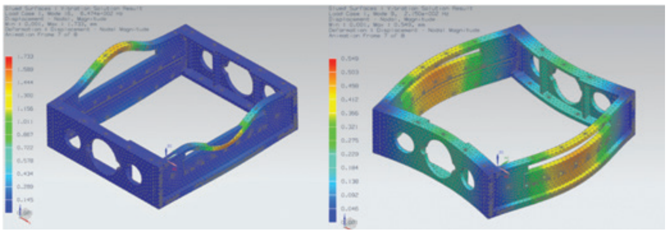
The existing µ4 prototype machine has been used to perform assessment of its diamond turning and micro-milling performance. For these tests the prototype was configured with air bearing rotary axes and needle roller bearing linear axes. Direct drive was applied to all axes. Achieved results were promising. Diamond turning of brass and aluminium substrates found 2-3 nm RMS roughness and 100nm P-V form for 32 mm diameter parts was easily gained. Diamond micro-milling was tested on aluminium substrates where sub 10 nm RMS roughness was achieved. Development of part programming processors to allow milling of down loaded images to be made quickly was performed in partnership with the Cranfield spin-out Loxham Precision.

Findings from this processing evaluation led to concern for the durability of the small gap and over-constrained rotary air bearing designs employed within µ4. Consequently, work has been started on revising the machine design by creating tailored rotary systems which will offer greater durability, higher dynamic performance and at lower cost. A UK based spindle manufacturing supply chain, initially developed for the R2R platform programme, is now being considered for future Meso scale platform rotary systems.

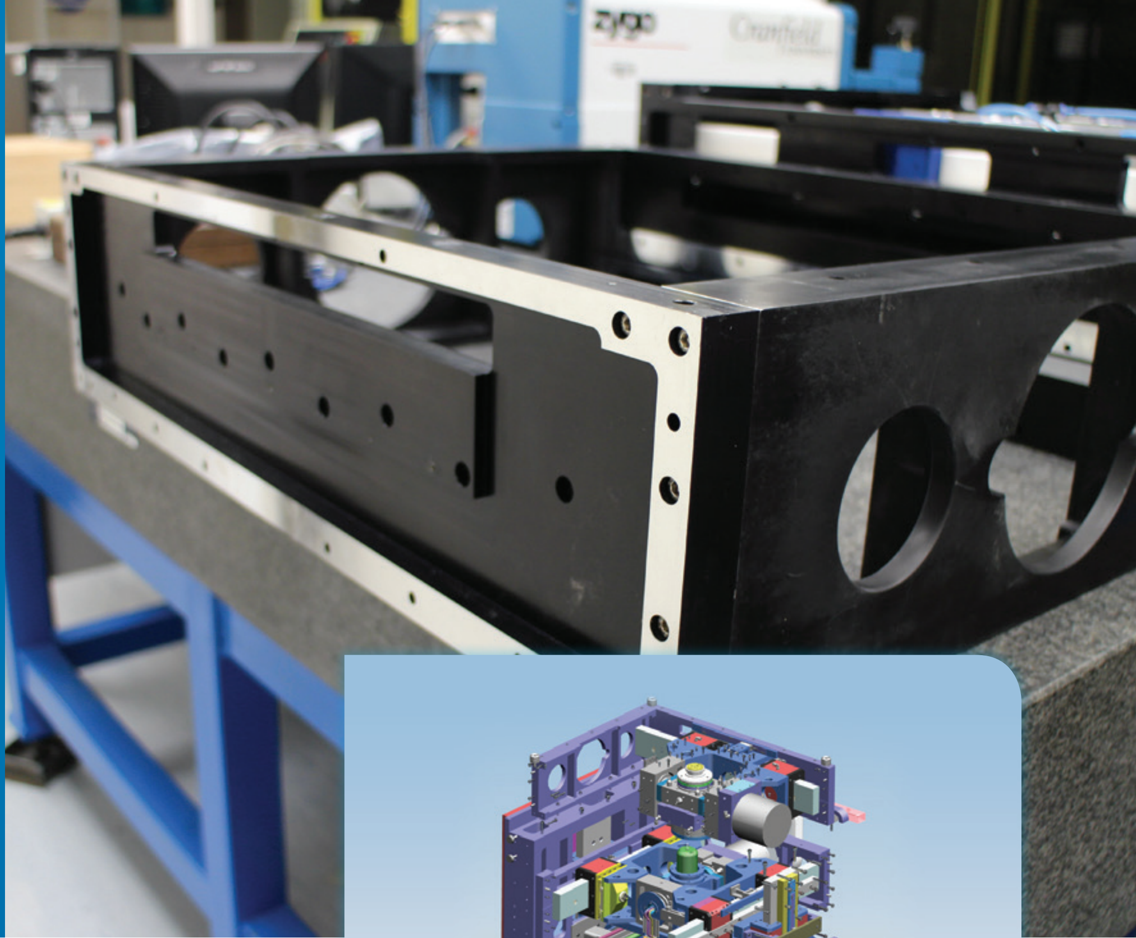
In depth analysis of the previous sourced rotary motion units, which gave rise for concern, has also started through an MSc student project which will be reported late 2014.

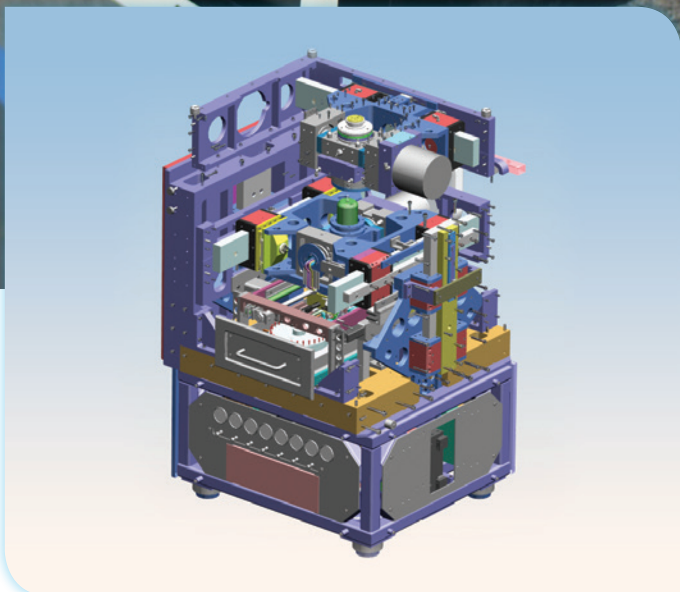
Dynamic Optimisation

Achieving high dynamic performance of the air bearing linear motions was initially defined as a key research topic to advance the Meso platform programme. Jonathan Abir, a mature PhD student, was allocated by the Centre to address this topic. Advancement of the dynamic performance and the tolerance to thermal changes were identified as key areas for advancement.



Detailed analysis of the main combined linear-rotary motion units of µ4 has progressed through the research of Jonathan Abir. Finite element analysis and modal testing has qualified the existing design.





Results are now being employed to revise the design to gain higher dynamic performance and ease manufacturing/assembly for future units. Key advancements will be performed with UK company Castech, who are being guided by simulation and dynamic test results.

From initial test work the stability and durability of the linear air bearing module was found to be dependent on the plates and assembly procedure employed to make the frame structures. Detailed metrology of these plate-like components indicated their tolerance build up was problematic for the air bearing design employed. A revision of both the system design and the employed manufacturing route was carried out. Findings indicated a revised design and new manufacturing approach should be established.

Consequently, a Cranfield MSc group project was tasked with creating an ultra-precision diamond fly cutting machine to perform precise finish machining of the Meso platforms linear axes frames. The achievement of this group project can be viewed online: www.youtube.com/watch?v=ph4yYxQeItE. This student group project was supported by Aerotech, Renishaw and Mitsubishi who provided the control system, linear motors, measuring encoders and drive amplifiers having a combined price of over £30,000. At the time of writing this report the performance of the created machine was being evaluated. Its long air bearing linear motor driven slideway being the critical machine motion.

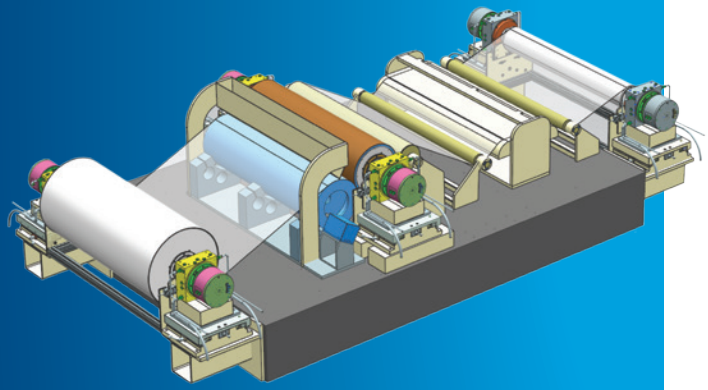
Automation and Metrology Integration

These topics were seen as being important in the short term to realise commercial benefits from µ4 and also in the longer term to be assured of small feature detection/adjustment. The automation and metrology activities applicable to the Meso platform are now also supported by a TSB funded project involving 4 UK companies from the UK precision manufacturing supply chain. This TSB part funded project represents an investment of over £600,000 into the Meso scale platform and will see a prototype machine under test in a UK production company in 2015.

In-situ metrology technology is being advanced through a Hexagon Metrology funded PhD student Jake Larsson.

Jake is presently undertaking a 6 month internship across 6 automotive companies after winning the Autocar Next Generation Award competition. See: http://www.telegraph.co.uk/motoring/news/10478063/Jake-Larsson-wins-2013-Autocar-Courland-Next-Generation-Award.html

Meanwhile progress of optical tool setting and automatic workpiece alignment systems have been made. A test rig facility has been constructed and initial tests undertaken.



Reel to Reel Platform

The Reel to Reel (R2R) platform is being created to realise 3 prime functional capabilities by the end of year 5 of the Centre. These are:

Provide a fully functional passive film embossing capability. This passive film capability should augment the micro texture roll fabrication facility developed under the previous EPSRC UPS^2 IKC. Achieving this specific capability will create a UK based World leading capability for producing novel 1.4 metre wide micro structured films applicable to a number of application research themes such as solar concentrator film, other light handling films, plastic electronic substrates, medical films and fashion/branding material.

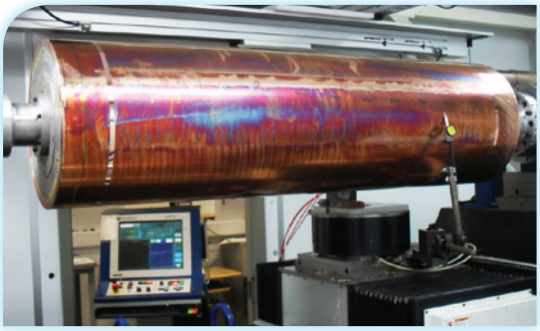
Create a world leading large scale film handling research motion platform capable of rapid ultra precision film handling and lamination research. This capability will allow both fundamental research and higher TRL development enabling the ESPRC Centre to drive the feature size scale applicable to film based products downwards as previously seen in the microelectronics sector under Moore's law.

Create a world leading large scale research platform capable of carrying out production process research applicable to film surface modification. The facility will allow production research of fine feature creation using processes such as imprinting, ink jet processing and laser processing.

Functional Requirement and Key Specifications

After undertaking a UK based road mapping event, a number of specialised meetings and evaluation of international road maps, a number of functional requirements were defined.

- The film width scale of the R2R platform was set by the largest width of roll capable of being diamond machined using the EPSRC UPS^2 IKS drum diamond turning facility. At this scale the R2R platform will be internationally leading.
- The positioning capability and the finest feature creation size have both been set at 0.001mm (1 micrometre). At this level it is 10 - 50 times better than the best reported industry reel to reel embossing capability.
- The maximum film speed of 5 metres per second is a ceiling level value for producing simple embossed passive films. For combined processing steps and precision lamination with active alignment a >3 metres per minute and 0.005 mm speed and accuracy target has been set.



Creation of Initial Film Web Handling Research Test Facility

This activity has been undertaken by a Cranfield MSc group project team. This test facility was produced with the support of Heidenhain GmbH, who supplied numerous high grade specification encoders. Fanuc UK provided the control system hardware and M-Solv advised about application demands. The facility is now being used to evaluate the complexities of precision motion control of thin films in 2 lateral directions. This activity secured industrial support of over £50,000 of donated hardware and in excess of 50 man days of technical support from the supporting companies.

Diamond Turning of Ultra Precision Micro-Textured Rolls

Although previously created under the EPSRC UPS^2 IKC, new activities under the EPSRC Centre for Innovative Manufacturing in Ultra Precision

Parallel research and major development activities

In defining the Functional Requirements for the R2R platform key machine specifications were established. It was also clear there were some knowledge gaps that demanded parallel research activity during the design and development of the R2R platform. **The top level programme considerations were as follows:**

- Film handling needs to be developed as an independent theme and a research facility needs to be created without consuming significant resources (people/funds) aimed at the R2R platform whilst also engaging a number of UK/international partners.
- A cost effective and responsive UK supply chain for large scale micro-textured rolls needs to be proven at fine feature levels ensuring cost effective large scale embossing rolls can be acquired. The roll fabrication route must include cost effective substrate fabrication and critically advanced coating processes offering consistent properties.
- Micrometre level motion control of large web films demand sub micrometre error motions of main rotary spindles whilst also having high radial load capacity for the heavy rolls ~200kg. Consequently, it was deemed necessary to employ hydrostatic bearings having ultra precision axis of rotation.
- Specific processes to be applied to the R2R platform would be developed through both research portfolio projects but also through partnerships with other research groups and industrial companies.

have now advanced the UK supply chain for creating large scale R2R mould rolls. Substrate and coatings capability for high performance rolls has been established and proven together with UK Company Keatings Specialist Cylinders Limited. Faster techniques to apply thick copper coatings directly onto aluminium roll substrates have been developed and verified. High aspect ratio features able to produce ~ 0.010 mm width grating features have progressed. An initial roll for producing film with embossed gratings has been created. It has numerous grating imparting characteristics that will enable fabrication of low cost scaled film. This grating film will satisfy the first objective of the R2R platform. The produced grating film itself will then be used within the web handling facility to further research motion control methods demanded to satisfy the second prime objective of the R2R platform.

Rotary Motion Technology

In order to ensure the R2R system would have the necessary precision rotary control at high load capacity and affordable levels, it was decided to design a new spindle concept and to create a new approach based on a new UK based manufacturing supply chain. Five UK companies (Castech, 3DE, Renishaw, Holford, Poeton) and one Swiss company (Etel) form the manufacturing supply chain to support the initial two prototype spindles. These spindles were designed exclusively within the EPSRC centre and are specified to have key performance benefits for rotating large rolls to sub micrometre levels accuracy of axis of rotation. An important research area is the performance of coatings as applied to the main load carrying features and the use of non conventional spindle materials to reduce fabrication costs. Progress to date is good. Spindle components have been fabricated and coated and are now being finalised to make ready for assembly and initial test. Two research students are currently engaged: Peter Xia on the coatings technologies and Gang Zhao on fluid film bearing technology.

R2R Processes and Platform

Progress on design the actual R2R platform has concentrated on the achievement of the first functional requirement.
The R2R platform design has also considered the additional systems necessary to add the second and third functional requirements. The design status of the R2R platform is indicated in the schematic figure. Progress on hardware is as follows: platform base is secured in partnership with Hexagon Metrology (second base is available with 8 week delivery), spindles are being finalised for assembly and test, initial grating roll is fully fabricated and is being surface structured, mountings for spindles are designed and under fabrication, and test hydraulics are ready for initial spindle performance tests.

R2R process technologies such as slot die embossing, laser processing and inkjet technologies are being established in partnership with a number of UK SME's. The initial slot die embossing process is being advanced together with iXscient Limited who will supply slot die technology, UV curing and film drying technologies. A number of other UK companies are expected to become involved during the remainder of Year 3 and Year 4 to provide necessary laser and inkjet process technologies.

The R&D Portfolio

The Research Portfolio is comprised of two heavily inter-linked strands focused on research into 'Ultra Precision Processes' and 'Ultra Precision Machines'. The research topics presented here are those that are currently in progress, and are considered to be of significant importance to the development of next generation ultra precision processes and products. These topics are delivered by both Cambridge and Cranfield students and are often directly related to the interests of our industrial collaborators. The Research Portfolio is kept under constant review and subject to periodic justification of the allocated resources.

Design and Build of an Ultra Precision Diamond Machining System

Sammy Yassine, Quentin Bonnardel, Domenico Sinsicalco, George Zaganas and Hangtian Zhou

This research was undertaken as a group project within the Centre at Cranfield by a group of Manufacturing Technology and Materials MSc students.

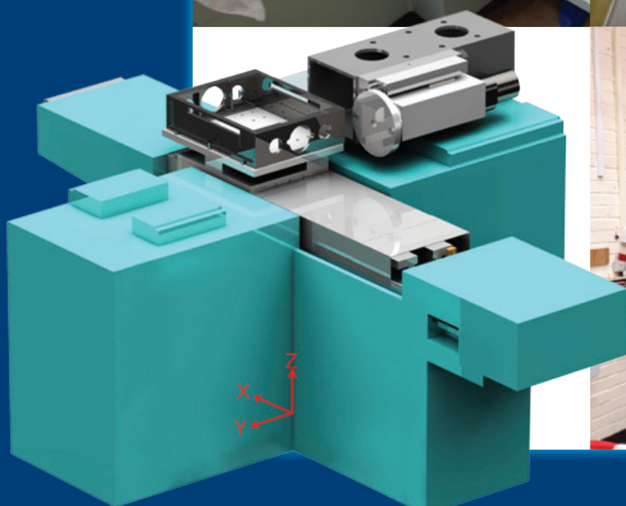
The project was linked to the meso platform, a highly compact 6 axes CNC ultra precision machining system. Its power density is high which demands its main structural components to be stress free after final machining. Those components have to be diamond machined with tolerances lower that what is achieved in the industry.

The aim of the project was to specify, design, build and test an ultra-precision diamond machining system in an almost impossible time scale (80 days, 60 working days). **The objectives were:**

- Specify, design, build and commission a diamond machining system in only 80 days
- Process an aluminium frame of 611 x 492 x 215 mm having 25 nanometre RMS roughness and flatness of less than 5 μm on four of its faces

The first step of the project was to define the diamond machining specifications. A complete review of an obsolete grinding machine was then conducted in order to identify components that could be re-used: air bearings and spindles.

The design process was carried out with a scope ranging from mechanical part design to electrical layout, using CAD modelling. Mechanical parts were sourced from suppliers. The control system and motors were complimentary from Aerotech, and Renishaw offered the two encoders.



Ultra Precision Light Sensor

Chris Williamson

The research in this project has been developing a novel method of ion beam patterning in order to position carbon nanotubes (CNTs) in a predetermined location. The CNTs were initially grown using an iron catalyst but the resultant structures were very fine and relied on Van der Waals forces to maintain their upright stance. Although a field of CNTs and patterning of the catalyst were achieved independently, combining the techniques together in an attempt to achieve freestanding aligned CNTs resulted in a lack of vertical alignment as shown in Figure 1. Figure 2 shows an attempt at massive growth on a silicon substrate with a nickel catalyst.

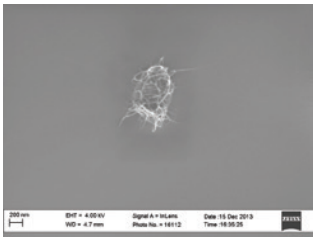


Fig 1 - First attempt at patterned CNTs

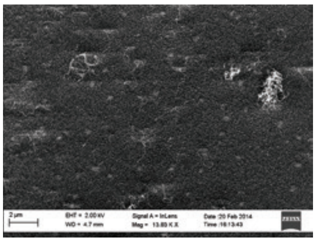


Fig 2 - CNT growth on nickel catalyst

It was determined that the lack of alignment could be due to insufficient structural stability in the CNT, a lack of a sufficient electric field or insufficient etching of the catalyst to form nanoparticles.

Different catalyst materials have been investigated to determine what effect they have on the resultant CNTs. It appears that the CNTs grow more efficiently using an iron catalyst but they are more uniform when a nickel catalyst is used. Nickel also yields tip growth whereby the carbon diffuses through the catalyst and grows downwards thus leaving a nickel particle on the top. Conversely iron exhibits growth from the base and also has a more random mixture of single and multiwall nanotubes.

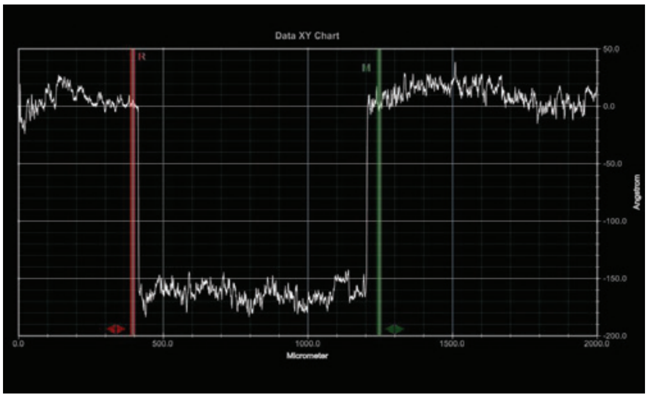


Fig 3 - Nickel layer calibration

In recent work nickel has been used as a catalyst and deposited using RF magnetron sputtering. This required calibration in order to deposit an accurate submicron layer thickness. Figure 3 shows the result of the profilometer measurement at 1000 seconds which yields a 15nm layer. Thicker catalyst layers result in wider diameter nanotubes and layer thicknesses can vary between 0.5nm and 20nm whilst still yielding CNTs. Since structural stability appeared to be an issue in the past, a thicker layer was chosen. Initial results of the CVD growth are shown in Figure 2 and there is a distinct lack of growth and alignment. This was determined to be due to an insufficient ammonia etch time before the carbon source was applied because there were no distinct catalytic nanoparticles. Using a 10 minute ammonia etch resulted in nickel islands as shown in Figure 4.

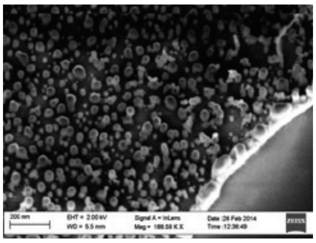


Fig 4 - Nickel nanoparticles after 10 minute NH3 etch

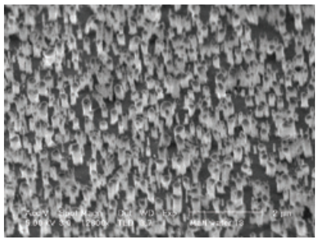


Fig 5 - Aligned CNTs

Figure 4 had the carbon source introduced for one minute and although it appears to have initiated some growth, it cannot be described as a nanotube. Before altering the growth time, the ratio of the acetylene and ammonia was varied from 20:160 - 100:160 to determine if the growth could be made more efficient. The results of this were not particularly clear although it seemed that the mid-range 50:160 ratio which was originally used yielded good island definition and the beginnings of CNT growth. Using this ratio of gas for 10 minutes after an initial etching of the nickel using ammonia at 580°C resulted in free standing aligned CNTs as shown in Figure 5. This result was obtained using an electric field between the substrate and the CVD gas shower head. When this field was removed, all alignment was lost and the adhesion of the nanotubes to the substrate was also poor. It can be seen that the diameter of the CNTs varies due to the random etching of the nickel layer into nanoparticles. A thinner layer is likely to split with a more even distribution, however the research undertaken is concerned with pre-patterning of the catalyst into a predetermined size (as in Figure 1) therefore the CNT diameter non uniformity is not a significant issue at this stage.

The next stage of the research will be to pattern the aligned nanotubes and look at their field emitting characteristics on vacuum pumped probe station which is currently being repaired and modified.

Holographic Enhancement of Fibre Optic Sensors

Jaliya Senanayake

A Fiber Optic Sensor is a device in which a light signal, relayed using optical fibre, is modulated by some interaction with a physical, chemical, biological or other measurand [1]. The modulation of this signal can then be used to measure (sense) the physical quantity or species which caused that modulation.

Fibre Optic Sensors offer a unique set of advantages over conventional electronic sensors. As dielectric devices they provide electrical isolation to the sensing environment, are immune to electromagnetic noise and may operate in high and variable electric fields without the need for heavy shielding. The basic transduction material, Silica, is largely untouched by most chemical and biological compounds, allowing for operation in corrosive environments, and with Silica having a very high melting temperature, devices may operate at greater dynamic temperature ranges than conventional electronic sensors. Furthermore, multi-sensor systems [2] are easily formed with a number of fibre sensors having common input and output fibre links, and Distributed sensing [3], where the measurand is interrogated along the whole length of a fibre by monitoring the output of the fibre alone is possible.

Since the first definitive papers on fibre optic sensing in the mid-1970s, today the technology has grown into a large scale industry with numerous realisations, ranging from bacterial growth monitoring to fibre optic gyroscopes. Commonly used sensing technologies include Micro-bend devices, Evanescent sensing, Fluorescent sensing, Surface Plasmon Resonance and Fibre Bragg Gratings. While extensive research is being carried out toward enhancing the performance of these sensors by various methods, one fundamental property of fibre has not yet been investigated.

Light propagates in fibre waveguides as a superposition of a number of fibre modes. No research has been performed to examine the effect of modal decomposition of light passing through a fibre, on its sensing ability. As different mode profiles have slightly different characteristics, it is expected that their sensing abilities would also differ. If the optimum modes for sensing of a particular fibre sensor can be identified, by only exciting these modes in the fibre, the sensitivity of the device may be increased. The goal of this research is then, to optimise the sensitivity of fibre optic sensors by controlling the modal decomposition of light within the fibre.

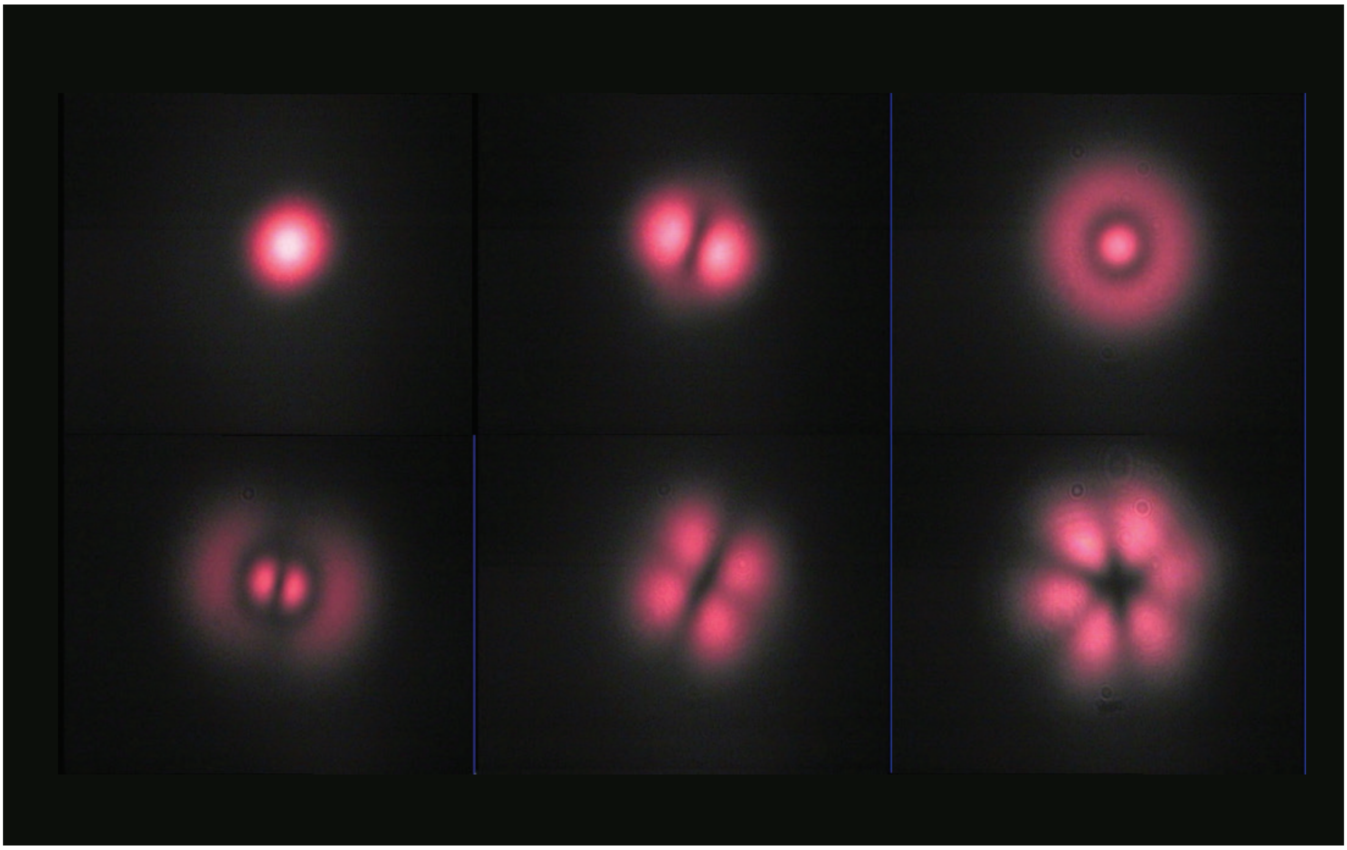


Fig 1

Modal control of the fibre is achieved using Holographic launch techniques. When light is incident on a fibre facet, the extent to which each fibre mode is excited is given by the 'overlap integral' between the mode field and the incident field. Using holography to control the full phase incident field, specific modes or combinations of modes may be excited with a suitable hologram. These holograms are generated by means of a Simulated annealing algorithm, which aims to maximise the overlap integral between the replay field of the hologram and the targeted mode field profile. Furthermore, the quality of the replay field is improved by using super resolution techniques.

The system is however extremely sensitive to optical aberrations, and to overcome this, a Zernike correction phase pattern comprising of the first 15 Zernike polynomials, is superposed on the hologram. To determine the coefficients of each Zernike polynomial, a sequential optimisation algorithm is used which aims to maximise the power coupled into the fibre.

Figure 1 shows the spatial light distribution at the output of a 2m SM2000 fibre, for launch conditions which target the various modes of the fibre. This demonstrates the effectiveness of the mode launch technique used.

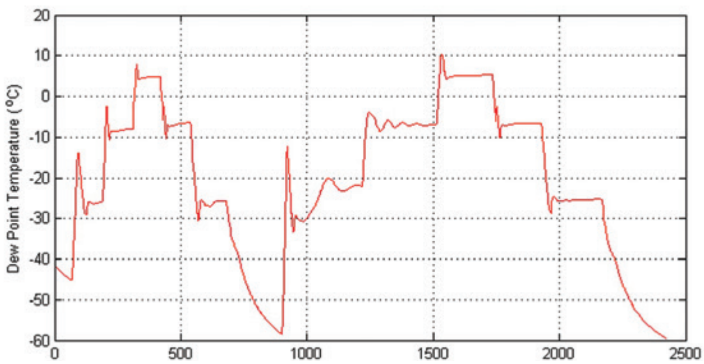


Fig 2

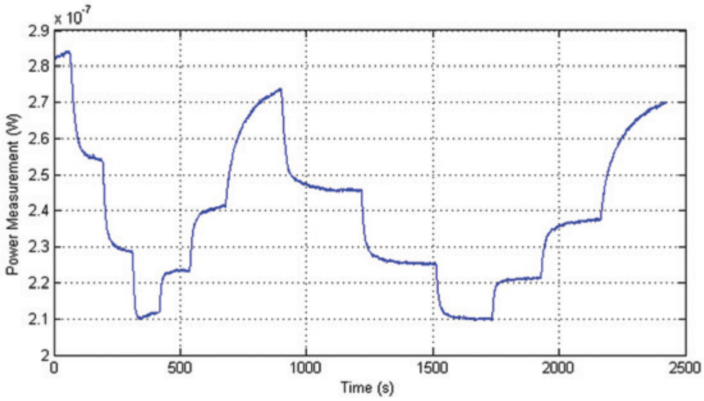


Fig 3

Experimentation is toward a humidity sensor of very high sensitivity. The proposed sensor for this is a fibre, side polished at the sensing region to expose the evanescent field. Changes in humidity at the sensing region alters the refractive index, which in turns affects the transmission characteristics of the fibre.

To demonstrate sensing, a variable humidity flow is generated using a dew point generator and directed to the sensing region of the fibre. The graph (Figure 2) shows the dew point temperature measured by the dew point generator, and the graph (Figure 3) shows the measured transmitted power of the fibre.

This shows the transmitted power is inversely related to the humidity and that the fibre is sensitive to humidity over dew points ranging from 5ºC to -60ºC. Although the overall power shift is small, launching different modes increases the power shift and therefore the sensitivity.

[1] B. Culshaw, "Optical Fiber Sensor Technologies: Opportunities and—Perhaps—Pitfalls," J. Light. Technol., vol. 22, no. 1, pp. 39–50, Jan. 2004.

[2] W. B. S. J. E. Udd, Fiber Optic Sensors: An Introduction for Engineers and Scientists, 2nd editio. John Wiley & Sons, 2011.

[3] M. Szustakowski and W. M. Ciurapinski, "Fiber optic distributed sensors," Optpelectronic Electron. Sensors II, pp. 12–17, 1997.

High Power Image Amplification

Jiho Han

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 1965, when Frieden[1] discussed a method for obtaining a top hat beam profile. Today, the techniques are well established, and are used for several applications [2]. However, for high power lasers, dynamic beam shaping solutions using active devices such as SLM are rather limited due to their modest power limits.

We consider the feasibility of amplifying a low power laser beam of arbitrary intensity profile into a beam of much higher power, while preserving the intensity profile. This would enable us to use low power devices such as SLMs to achieve the end result of a high power laser system with a built in dynamic beam shaping solutions.

The idea of image amplification dates back to 1958, when Schawlow and Townes[3] discuss the concept in their paper speculating the extension of maser technique into infrared and visible region. A simple arrangement may use a gain medium before the light reaches the image plane to obtain image amplification. The obvious problem with this arrangement is the rather modest gain that results from a mere single pass through the active medium.

In order to increase the gain, a multi-pass arrangement or an optical cavity can be used to let the light through the gain medium several times. A so called self-imaging cavity can be used to retain an arbitrary transverse beam profile after one round trip within a cavity. Similar arrangement referred to as active imaging was discussed by Myers, Wieder, and Pole[4], where they inserted a gain medium within a 4f arrangement and place a mask in front of one of the mirror to obtain a laser from which emerges the beam shaped as the mask.

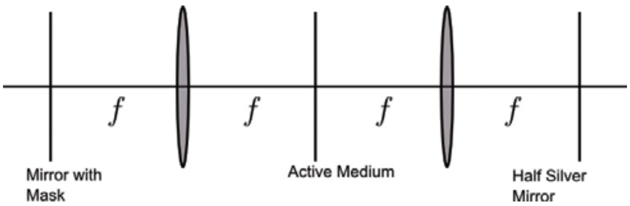


Fig 1

However, the considerations for image transmission through self-imaging cavities were not made until 2005[5]. Chalopin et al.[6] present an interesting work following this, where an image is frequency doubled by passing it through a doubling crystal within a cavity. One may speculate the feasibility of using an active medium to amplify the image arbitrarily, however no evidence of such publication was found so far.

We propose the arrangement where a self-imaging cavity and a laser gain medium is used to amplify a transverse image of a low power beam, in order to achieve the end result of a high power laser with a built in dynamic beam shaping solution. Many conventional laser designs can be modified to achieve this; an isolator-like arrangement is necessary to separate the input and the output and the cavity must be modified into a self-imaging cavity. Shown in figure 2 is a conventional regenerative amplifier arrangement modified in this way. Alternatively, a ring resonator could be used to naturally separate the input and output.

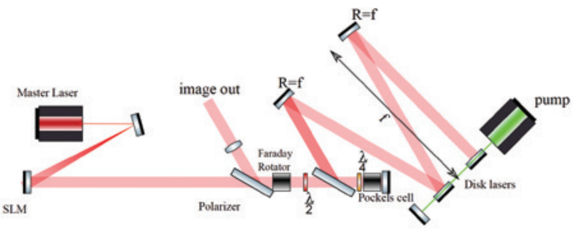


Fig 2

Other possible amplification method includes Optical Parametric Amplifiers and amplification by a single pass through a multimode fibre, with controlled mode mixing. These methods will also be investigated.

A number of obvious challenges are as follows: 1) The arbitrariness of input beam profile means that there exists a beam profiles which allow it to focus somewhere within the laser cavity. This must be avoided in order to prevent damage within the laser. 2) The image amplification relies on the image being reconstructed after a round trip. A small error in the imaging may completely void amplification conditions. 3) With the laser above lasing threshold, the stimulated emission will be amplified and behave as a normal laser, even for the part of the imaging field where 0 intensity is desired. It follows that an additional control is required to ensure that optical oscillation is supressed where it is not desired. Trivial solution is to place an aperture inside the cavity as in Myers, Wieder, and Pole[4], but of course this voids dynamic operation, and may be unsuitable for high power lasers.

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

Jonathan Abir

The project is focused on technologies that allow free-form surfaces manufacturing with the constraints of a compact machine tool. The research will be made by design and development of a mechatronic system leading to high-dynamic motional control of compact machine tool as required for free-form manufacturing. The research findings will be implemented within the μ4 machine made by Cranfield University Precision Engineering Institute and Loxham Precision Ltd. Through this research, investigation and analysis of mechatronic designs shall be performed as well as experimental work. The experimental work will include system identification and validation before and after the implementation of improvements to the μ4 machine. The contribution to knowledge and the novelty of this research comes from combining the apparent antagonistic requirements of small size machine and free-form surfaces into one solution based on experimental and simulation work.

The μ4 motion axes were split into two nearly identical modules. Thus, each module can be used as a test rig to identify and specify the current design and to validate the improvements during this research. The system identification methodology is a bottom-up process in which the lowest level components are tested and simulated first, then used to facilitate the testing of higher level components.

The modal properties of the motion axes module were simulated using Finite Element Method (FEM), measured and analyzed using modal measurement equipment specified and procured for this research. Each component and assembly was suspended in free-free conditions and frequency response functions measured using hammer excitation. Rigid and flexible body modes were synthesized using least squares complex exponential stabilization diagrams choosing the frequency and damping values. The results were validated by observing the animation of the modes and by comparing the properties to those of a FEM. The FEM results (frequency and mode shapes) showed a good correlation to the measurements. The modal results will be used as an input to the improved mechanical design and will help implementing technologies which will achieve the high dynamic motional control goal. Furthermore, the FEM-measurements correlation can now be used to simulate the performance of the improved motion axes module.

The next phase of the project will be focused on investigating which technology and techniques should be used in order to achieve high-dynamic motional control. Several solutions are considered – innovative mechanical design, neural network based on low-cost measurement components, or a feed forward control design.

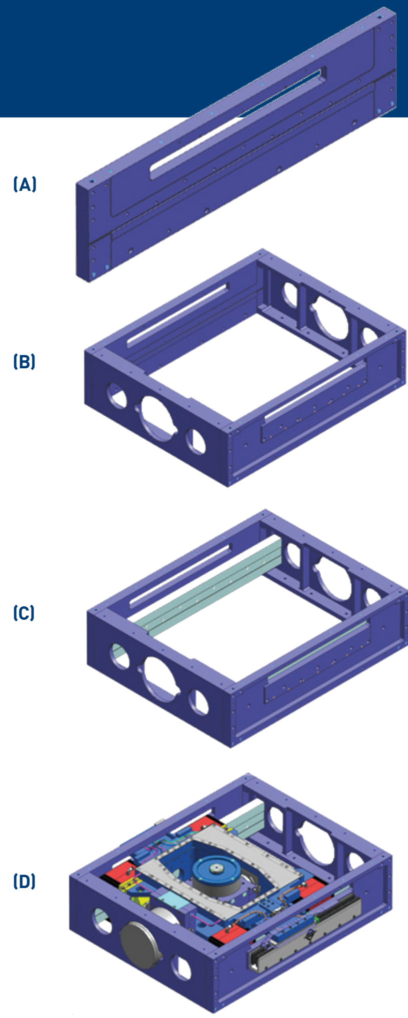


Fig 2 - System Identification Methodology

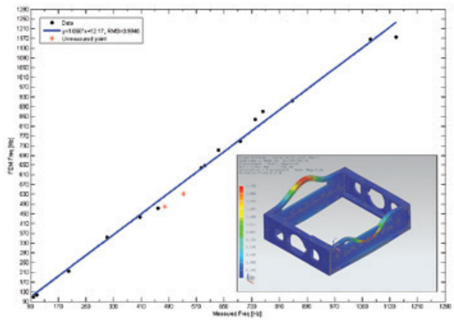


Fig 3 - FEM and Measurement Correlation

Fig 1 - Motion Module

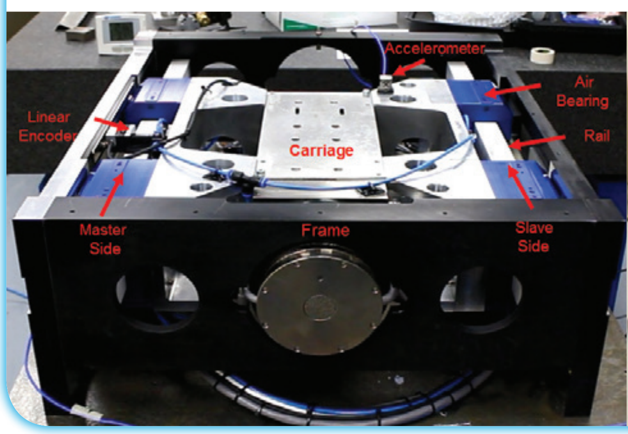
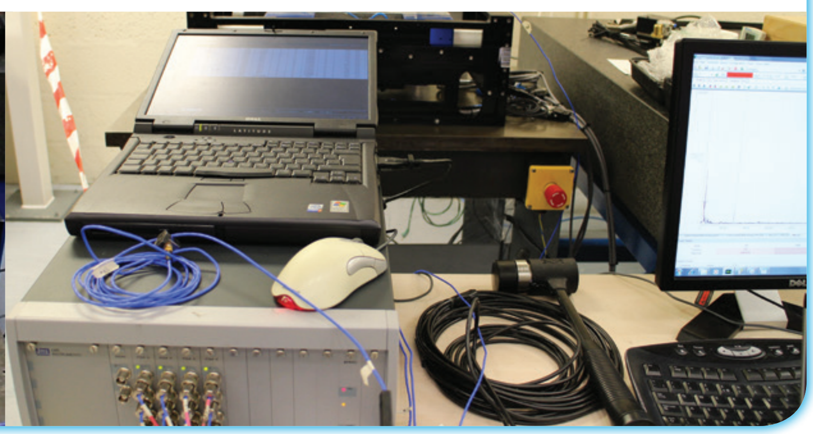


Fig 4 - Modal measurements



Optical Quality Wear Resistant and Diamond Turnable Coatings

Peter Xia

Hydrostatic bearings and structured rollers are production machine components used in the reel to reel production of plastic and electronic parts. The bearings are presently made from aluminium and the rollers of aluminium or steel. Both bearings and rollers undergo a certain degree of diamond machining, either on the actual "bearing" surfaces in the case of bearing assemblies or as a myriad of micro-features (of optical quality) that form the structured surface of the rollers. The latter micro-features are subsequently replicated into target materials during the reel to reel production process.

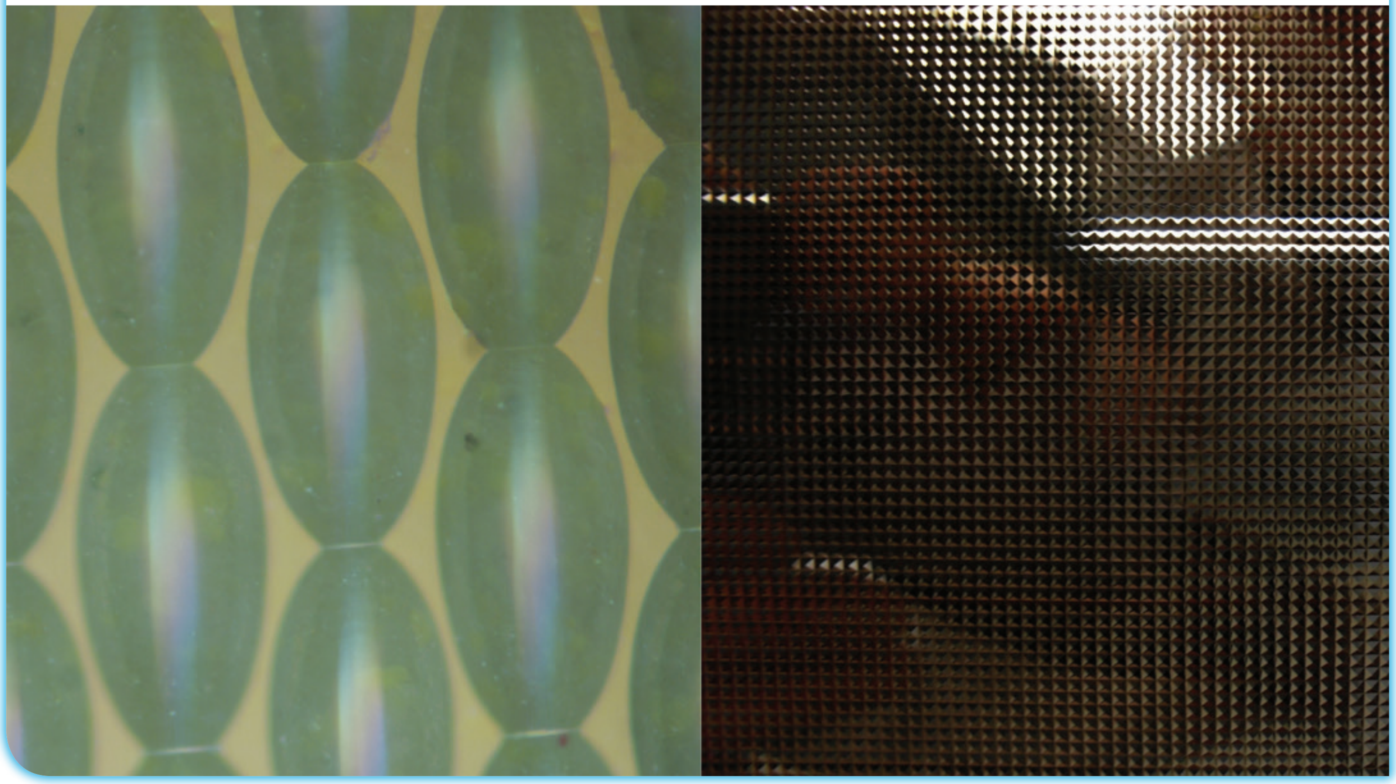
Bearings parts and rollers are typically coated nickel on the bearings and copper or nickel on the rollers. Although, the coatings provide wear resistance, they serve another important function, particularly in the case of the rollers. They provide a coating of sufficient thickness into which micro-features of high aspect ratio can be diamond machined. Copper, although not as hard wearing as nickel, is better from a tool-life perspective during this machining process and has proved particularly useful in a prototyping capacity. However, nickel's better wear characteristics have a distinct advantage for the subsequent replication process.

Nickel as applied by the electroless process has the ability to provide a conformal coating without the characteristic build-up of material at edges and high points of the conventional electroplating process. However, there is a problem with porosity when trying to achieve the necessary thickness required to incorporate high aspect ratio micro-features. Additionally, stray particulate matter settling on the roller during the actual plating process will be replicated with great fidelity within the coating. Both porosity and such defects cause problems during the diamond machining process.

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. In doing so, it should be possible to enhance quality and reduce the defect rate of rollers and hydrostatic bearings, both of which can be considered high value, low volume and technically demanding components. In terms of the subsequent reel to reel manufacture, these components are ultimately integral in producing thousands of parts.

To date, possible bath compositions have been identified in order to undertake in-house experiments, possible alternative coatings have been identified and currently, investigations are being made in order to benchmark "in-house" plated samples and externally-supplied plated samples, in order to understand what constitutes a "good quality" coating in terms of its ability to be diamond machined.

Example of diamond turned structured surface (micro lens array (left) and pyramid structure (right)



Production of Carbon Nanotube Based Cold Field Emission Cathodes

Francisco Orozco

Sponsor: **Air Force Office of Scientific Research**

Cold and thermionic are types of electron emission. Some applications for these emission sources are X-ray systems, point sources for electron beams, displays, and lamps (Niels De Jonge and Bonard 2004). Thermionic field emission cathodes operate at high temperatures often giving inefficient power utilisation, poor reliability and an inadequate lifetime. The need for device thermal management adds to the complexity and weight of these devices. Cold emission is more energy efficient due to lower turn-on voltage which translates to less thermal management. This allows for the sources to be miniaturized giving new applications such as hand held X-ray devices. Cold cathodes are already starting to replace thermionic emission cathodes (F. Charbonnier 1996), however new cathode materials are needed that are reliable over the long term, emitting high currents (>10 mA) at low temperatures (<1000°C) with a low turn on field (Lahiri et al. 2010).

Work proposed investigates the application and development of carbon nanotubes (CNT) as cold cathodes. CNT show good emission properties are chemically inert and can be produced in large quantities. These are machined by a laser source producing geometries favourable for emission. The use of a laser presents a capable solution to cut the material in a controlled manner shown in Figures 1 and 2.

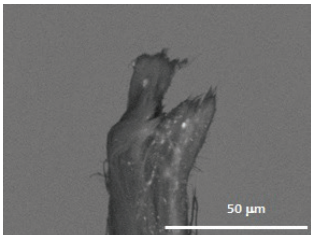


Fig 1

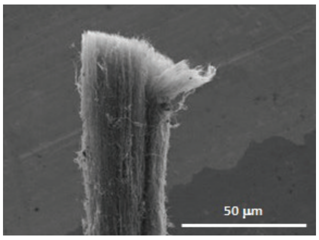


Fig 2

The research line for this project has two main branches. The first is the study of laser-matter interaction. These studies will provide benefits which can be denoted for instance as a higher emission capability or a reduction of the turn on voltage. This branch will be divided into two parts. The first subsection aims to reduce the damage made to the carbon nanotubes when being cut. The second subsection includes an optimization of geometry for arrays and single emitters to enhance field emission.

One of the main difficulties for production is the handling of CNT based films and fibres. The second branch of this project will focus on the development of a scalable production route that overcomes the manufacturing challenges for carbon nanotube based cathodes.

Initial studies compared two laser sources to observe differences in the laser-matter interaction which could affect emission properties of the CNT. One of the lasers had longer pulse duration (200 ns) while the second one had shorter pulse duration (130 fs). The results of the emissions of both samples are presented in Figure 3.

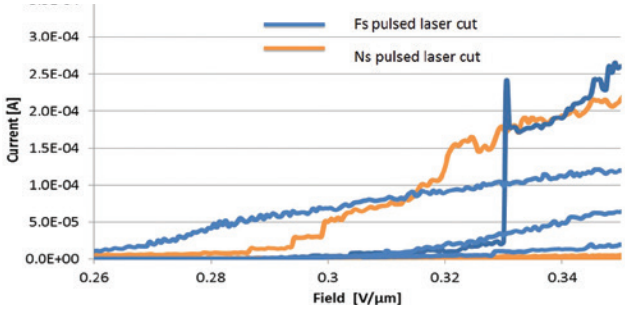


Fig 3 - Both samples had the same shape and they came from the same batch of CNT film the only difference was the laser used.

We have demonstrated a reduction in the turn on voltage on CNT films by processing with an ultra-fast laser. This result is attributed to the lower heat affected zone created by ultra-short pulses and multi-photon absorption of the material. As the interaction between the carbon nanotubes and an ultra-fast laser source is not fully understood, this research will aim to obtain a further comprehension of this interaction and implementation.

To address the production problems handling techniques must be established. The films are around 30-50 µm thick which makes the material susceptible to environmental (i.e. small currents of air, moisture) and electrostatic forces. While machining, the film needs to be flat (±8 µm) to remain at the focus of the laser beam. Another identified problem is the alignment of the emitters. The emission points are required to have ideally the same distance to the anode. Not doing so compromises the electric field distribution giving unstable emission and early failures to the points with higher emission when the field is increased. Having a dispersion of more than 4% in the CNT produces a reduction of the emission properties (Niels De Jonge and Bonard 2004). Arrays are being created by stacking the films together. This is also a key factor in the alignment due to the previously mentioned problems. Once processed the films are sent to the United States for emission characterization. The samples must be able to maintain integrity until arrival to the test facilities. This gives an opportunity to have a real world problem in handling that allows testing of fixtures, bonding of the material, sturdiness in the alignment as well as outer packaging of the devices.

Continued overleaf

The highest emission current achieved so far by these arrays was 7.6 mA shown in Figure 4.

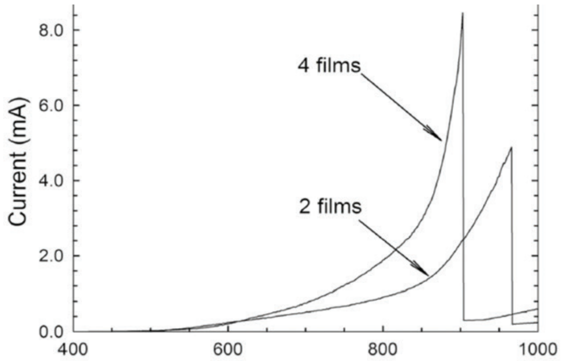


Fig 4 - This graph shows the emission that has been achieved by stacking several films of emitters creating a larger array

As seen in the image increasing the voltage led to a failure in the devices, emission current dropped almost to cero. However increasing more the voltage showed that the emission current started to rise again. This represents that emission points changed to a larger area which is presumably due to delamination of the film.

Material handling is one of the primary difficulties of this project, overcoming them will lead to a consolidated production process. Current research is looking into the application of coatings onto the substrate which are compatible and could potentially enhance field emission capabilities. Talks are being held with other research groups who have expertise in coatings to achieve the best results in the shortest time. Another solution being considered is to mount the CNT films onto a substrate for processing. However it is unclear if the carbon nanotube's field emission properties are jeopardized considering the substrate material could give off impurities to the emission areas while being machined. This part of studies is scheduled to begin in the second quarter of 2014.

The background activities that have been held are state of the art search, gaining knowledge about the CNT material properties. Interaction of compounds with the CNT and how these can change the material properties for emission as well as the mechanical benefits of coating the material.

A robust amount of data has been gathered and part of it has been published in the form of a paper which has been published in the Journal of Materials Research, Focus Issue "Graphene and beyond". The journal requested to use an image of one of the samples machined at Cambridge to be used in the cover page of this issue.

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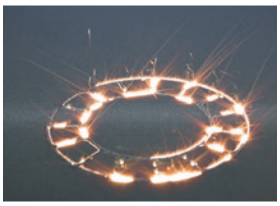
Increasing Throughput of Laser Additive Manufacturing in Metal Powders for Biomedical Applications

Jonathon Parkins

Sponsor: **Stryker, The Leete Premium Award and The Engineers Trus**

State-of-the-art fabrication technologies for production of biomedical implants use additive manufacturing techniques to create strong, porous and complex structures from biocompatible materials such as titanium or Ti-6Al-4V alloy [1]. Two main technologies are implemented to meet the demands of the industry: electron beam melting (EBM) [2], [3] and selective laser melting (SLM) [2], [4]. The properties of these technologies are given in Table 1.



Fundamental limitations on the electron beam process such as the vacuum requirement and the coulomb interactions in high power electron beams cannot be changed. However, laser technology has scope for process speed improvement; there is no fundamental reason why laser throughput cannot be increased. Laser melting can be the industry-leading technology if this issue is addressed.

The aim of the project is to develop a technology capability that increases selective laser melting part throughput over current galvanometer-based systems.

SLM	EBM
✔ Good surface finish on parts	✔ Extremely high process speed
✔ High resolution at high scan speed	✔ Low residual stresses – little bending
✔ No need for vacuum	✔ Freeform, multi-component build
✘ Relatively slow scanning	✘ Vacuum required
✘ High residual stresses	✘ Slower speed for high resolution (due to coulomb forces at high powers)
✘ Less advanced preheating	✘ Poor surface quality
✘ Parts need supports	✘ 10 % of builds fail

Table 1 - Advantages and disadvantages of metal additive manufacturing technologies.

Beam delivery technologies have been assessed:

- Galvanometer scanners. Current state-of-the-art additive manufacturing systems use galvanometer driven mirrors in two axes to scan a laser beam. They are limited by acceleration and deceleration of the mirrors.
- Multiple galvanometer approach. Utilising multiple galvanometer scan heads can increase the scan capabilities proportionally. This also increases processing flexibility. The cost and physical arrangement of multiple heads limit their implementation.
- Light modulators. Micromirror arrays and liquid crystal modulators can generate arbitrarily shaped beams to expose localised powder regions simultaneously. The power handling capability and resolution are limited.
- Acousto-optic deflectors. Acousto-optic deflectors use standing waves in crystals to diffract and change the laser position. These devices perform rapid scanning with no mechanical lag. They are limited by small scan ranges, power handling capability and low efficiency.
- Polygon scanners. Rotating polygonal mirrors scan along a single axis at up to 200 ms-1. The larger minimum feature size and the physical device size limit their use.

Different processing approaches have been considered with collaborative industrial feedback:

- Single exposure of whole bed. Projecting a patterned beam onto the whole powder bed simultaneously to melt layers in the minimum possible time.
- Single exposure of small area then motion. Projecting a patterned beam onto a single area (one part size) then moving the beam to a subsequent processing region.
- Whole bed scanning. Positioning the scan technology above the bed such that all regions of the bed can be scanned by a laser beam. The two methods are:
  - Raster scanning. The beam moves slowly across the bed scanning lines rapidly
  - Vector scanning. The beam can be moved in any direction by a combination of two axes of motion from the scan technology
- Small area scanning then motion. The area of one part or smaller is rapidly scanned locally then the scan technology is moved across the bed to a new process region. Again, there are two scan methods that can be used:
  - Local rastering
  - Local vectoring

The bed fill factor of parts will determine the technology choice, as this will define the duty cycle of the process. The most likely optical configuration for full bed scanning of dense parts is a polygon raster scanner with a galvanometer scanner for fine featuring. Acousto-optic deflectors can fine feature if a 'single part then move' strategy is used. The multiple galvanometer approach is a fast and tunable system but is being explored by another research group. A custom light modulation technology may be explored to handle high power lasers to expose part by part.

The next step is to define a specific fabrication approach and technology based on a specific biomedical component with high manufacturing demand. The technology will be developed for additive manufacturing including an electrical, mechanical and optical design. A control system will be created and implemented. The system performance will be characterised. A biomedical implant part will be fabricated and the performance and properties of the part tested. The suitability of the technology for biomedical implant fabrication will be assessed.

Jon Parkins has been awarded the Leete Premium Award from the Worshipful Company of Engineers in support of this PhD project. The award, newly established for this academic year, supports excellence in production engineering research. It will support Jon in his research towards development of laser additive manufacturing capability, in particular with application to the biomedical implants industry.

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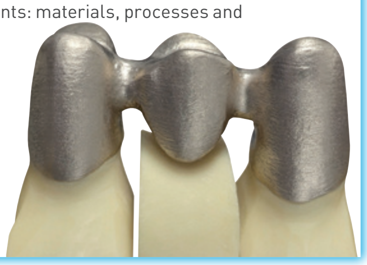


The Use of Ultrafast Laser Annealing for the Removal of Ion Beam Implanted Gallium

Matt Bannister

The Focused Ion Beam (FIB) is an extremely useful and versatile micro-machining tool, with which material can be deposited onto a surface, implanted within a target or be used to mill features in a target substrate. Gallium is often the ion source of choice due to many desirable properties – a low melting point (so it may be kept liquid with minimal heating), a low volatility which allows it to have a long storage lifetime, and a sufficient atomic mass to machine heavy elements while not causing excessive damage to lighter element targets.

The interaction process between the accelerated ions and the substrate results in gallium ions being implanted within the target, with the ion distribution depending on factors such as the beam energy, target atomic number and crystallographic orientation. Above a critical ion dose, crystalline regions may also be made amorphous. This, as well as ion implantation, changes many properties of the target substrate; these include surface hardness and chemical reactivity, electrical conductivity, optical absorption and many others. As a result of ion implantation, the target substrate may no longer be fit for the purpose it was originally intended for, and limits the scope of FIB manufacturing. This project aims to remove ion beam implanted gallium ions from the surface of various substrates in order to reverse many of these property changes, and increase the range of applications of ion beam manufacturing.

Ultrafast laser pulses below the damage threshold of the material are used to anneal out the implanted species. By using ultrafast laser pulses, any material changes caused are confined to the focal volume of the laser. This is because the timescale on which thermal events occur are significantly longer than the duration of the laser pulse, which is of the order of a few hundred femtoseconds. This is advantageous as it allows higher precision control of the annealing process, and also permits annealing of devices containing thermally sensitive components that may be damaged by using longer duration laser pulses or conventional thermal annealing techniques. A review of literature has identified a mechanism by which ultrafast laser annealing is thought to take place. Laser pulses are absorbed by the substrate through multiphoton absorption. This energy promotes electrons to the valence band, and when a high enough proportion (10% or more) become excited, ultrafast melting of the substrate occurs within the focal volume. During the liquid stage, gallium ions are free to diffuse away from the surface along a concentration gradient. Re-solidification of the substrate then occurs once the laser source is removed, with the crystalline structure reforming based on liquid phase epitaxy.

Preliminary investigations have been carried out using glassy carbon and silicon as examples of amorphous and crystalline materials. In these investigations, gallium was implanted into substrates at doses ranging from 10^{18} to 10^{20} ions/cm^2. Annealing was carried out by scanning the laser beam at 1 mm/s at a fluence below that of the experimentally determined damage threshold. The laser used was an 800 nm Ti:Sapphire laser, with pulse duration < 150 fs, with fluences of approximately 5 μJ/cm^2. After annealing with the laser, the surface potential of the implanted substrates was measured using Kelvin probe force microscopy (KPFM). By mapping the surface potential with the KPFM, relative changes in surface potential due to the change in gallium ion concentration were made. An example KPFM profile is shown in figure 1. The left hand profile shows a surface potential of approximately 38 mV across a region of glassy carbon implanted with gallium at a dose of 1.87 x 10^{20} ions/cm^2. The right hand profile shows a profile across this implanted region after annealing with an 800 nm Ti:Sapphie laser at a fluence of 5.4 μJ/cm^2. These results indicate that gallium was removed due to annealing by ultrafast laser pulses. In the case of silicon, no changes in surface potential were observed. However white light reflection imaging of the silicon substrate indicated changes in refractive index of the annealed areas due to re crystallisation of the amorphous region created during ion bombardment.

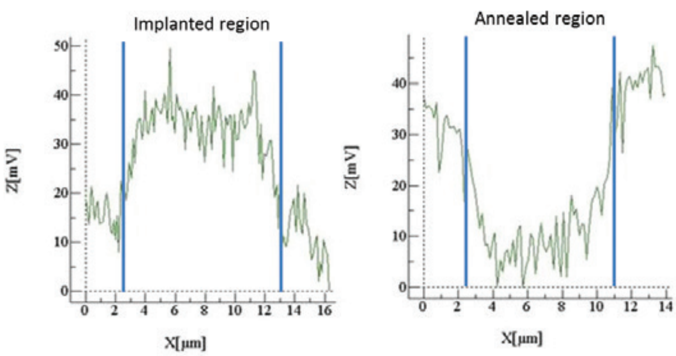


Fig 1 - KPFM profiles of glassy carbon implanted with gallium ions at a dose of 1.87 x 10^{20} ions/cm^2 across a ~10 μm wide region. Left – profile across implanted region. Right – profile across implanted region after annealing with ultrafast laser pulses

From literature, several factors have been identified which may influence the ultrafast laser annealing process and require detailed investigation to elucidate the effects on gallium distribution. These include the laser pulse fluence, pulse duration, laser wavelength and substrate temperature. The effects of laser pulse fluence on the distribution of ion beam implanted gallium are currently under investigation. Gallium ions were implanted into glassy carbon and silicon at doses ranging from 10^{18} to 10^{21} ions/cm^2 and annealing

Sponsor: **Carl Zeiss**

carried out using an ytterbium fibre laser (wavelength 1030 nm and pulse duration 280 fs). Pulse fluences were varied between 0.39 and 0.09 J/cm^2; below the experimentally determined damage threshold. Initial analysis by KPFM was found to be time consuming, unreliable and unrepeatable, and so an alternative measurement technique has been selected. Energy dispersive x-ray spectroscopy (EDS) is a fast surface analytical technique, and is able to provide a quantitative composition analysis of the substrates to within 0.1% accuracy, with a lower detection limit of 0.5%. Gallium ion distribution after ultrafast laser annealing has been measured using EDS; however it was found that the implantation doses used in this investigation were too low for reliable detection. Additionally locating the annealed locations within the implanted regions was difficult, and as such the experimental technique requires further refinement. This requires a higher implantation dose, and also some form of fiducial marker to identify the annealed region. Investigations of the effects of laser fluence are expected to be completed by the end of April 2014.

One of the major aims of this research is to develop and validate a model explaining the gallium distribution within the implanted substrates after annealing. This shall be carried out using data gathered about the effects of laser process parameters – the laser pulse fluence is currently under investigation and, once completed, other parameters are to be investigated. The laser pulse duration is to be varied using an external pulse compressor and monitored using autocorrelation. The effects of wavelength shall be investigated using a triple-wavelength laser, which produces long wavelength ultra-violet, green and infra-red picosecond pulses. Analysis of these parameters is expected to be completed by September 2014. The location of the migrated gallium is currently unknown, and studies shall be carried out to determine if migration is occurring further into the substrate, or out of the surface. A comparison between conventional furnace thermal annealing shall also be carried out, as well as an investigation of any changes in surface topography caused by ultrafast laser annealing, to ensure any alterations in FIB machined features are minimised.

Control System for Ultra Precision Processing

Karen X.Z. Yu

Sponsor: **IPG Photonics**

Rapid manufacturing at small scales dictates the need for integrated measurement during processing. Without this, small variations such as changes in temperature or substrate material will have significant effects on the final components produced. Many of these uncertainties will vary by only single microns or less, no consequence in macro manufacturing (e.g. installing a car door) but catastrophic on the scales used here (e.g. lab-on-chip blood analyzers). The aim of this project is to utilize a number of analysis techniques for high and low speed in process inspection. The proposed system will also have an integrated control strategy with various options for optimizing either cost or performance.

Figure 1 shows the control flow diagram for proposed system along with dates of when each component will be completed. Figure 1 also shows the selected imaging modalities: optical microscopy (most cost effective), optical coherence tomography (OCT, midrange high speed point inspection), and digital holographic microscopy (DHM, full 3D in-situ imaging).

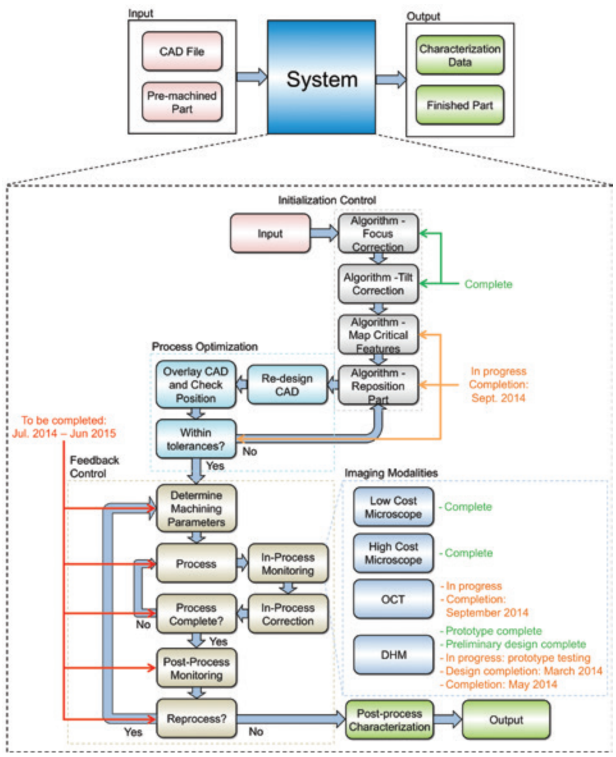


Fig 1 - Control flow diagram of proposed ultra precision processing system.

1) Optical Large Area

Optical microscopy gives the most cost-effective

Continued overleaf

solution but has limited capability to provide 3D information (through focus). Here, the industry has the option to choose the microscope that best suits them, e.g. dark field, high magnification, large field of view. The control code will be easily adaptable to each microscope with minor calibration required between systems. Control algorithms have been developed with images from a low magnification optical microscope. A high magnification microscope has been surveyed that provides performance suited for ultra precision and highlight challenges in calibrating the code between different microscopes.

2) Optical Single Point

OCT is a midrange option that provides high-speed in-line and *in-situ* point inspection. For applications where placement of blind holes can be sufficiently controlled by stages, OCT gives rapid feedback of hole depth and if a through hole has been achieved. At present, a review of the technology and limitations of specific variations (i.e. Spectral Domain vs. Swept Source) has been conducted with design and construction to begin in the following months. 3D OCT is possible, but at increased cost and decreased imaging rates. The nature of OCT also prohibits acquisition of the whole 3D space at once, i.e. a scanner is required where the first and last point of the image would be acquired at different times (dependent on scan speed and image size).

A reflection DHM system will be designed for this project; a transmission system would not be usable unless the processing material was highly transparent. A prototype DHM system has been completed (see Figure 2) and is being tested. Table 1 shows the parameters targets for each version of the prototype and final system. Specifically, the prototype allows testing of a Michaelson and Mach-Zender setup (i.e. on- and off-axis DHM respectively). The system also allows testing of image reconstruction algorithms that have been developed.

Parameters	Prototype 1	Prototype 2	FINAL
Depth of field	~260 nm	~1.5 µm	5 µm
Axial resolution	< 20 nm	< 20 nm	50 nm
Lateral resolution	~1.7 µm	~1.7 µm	500 nm
Number of wavelengths	1 (532 nm)	2 (532 nm and 650 nm)	2-3
Incorporate control code?	No	Yes	Yes

Table 1 - Target specifications for prototype and final DHM systems.

Similar to OCT, The DHM system will be in-line with the processing beam and capture real time images during processing. DHM has the added advantage of generating full 3D data, giving the system information about the overall part and allowing for better control (e.g. better positioning with respect to fiducial markers). One issue at present is the slow image processing rates for DHM, which will limit real time feedback. This is both a software and hardware limitation that may be improved by moving the image processing onto the GPU.

Several algorithms have been developed in keeping with the aim of a modularized system, where the codes are not specific to metrology.

Thus far, an imaging focus find and tilt control algorithm has been completed. First, a stack of images is taken in Z where each image is filtered and thresholded. Edge detection is also applied, which is used to identify distinct regions of the image. From this, it has been found that the stack with the highest number of regions corresponds to the focus. Figure 3 shows experimental data for the focus find algorithm. The data also appears to fit a Cauchy-Lorentz curve, which may be used to better determine the focus of the image.

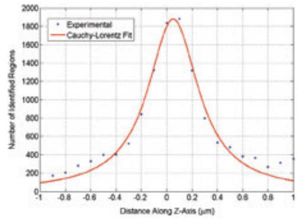


Fig 3 - Image of focus find test data

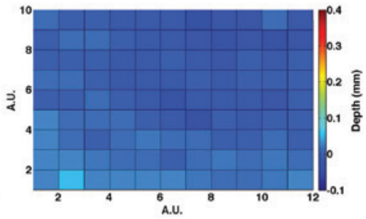


Fig 4 - Segmented focus find for tilt control. There is a slight tilt from the bottom left to top right and can be seen by the change in the shade of blue

The focus find technique described has also been adapted for tilt control. Each image of the stack is segmented into smaller regions where a focus find is conducted on each region. Figure 4 shows the results of the tilt control and it can be seen that there is a slight tilt for this sample from the bottom left to the top right corner. A further application would be to define very small regions, which allows some structural features to be identified and may be used to give a rough 3D profile. Figure 5 shows a) an in-focus optical image, and b) a high segmentation image. Certain features from the optical image can be identified though at present the process suffers from a high degree of noise.

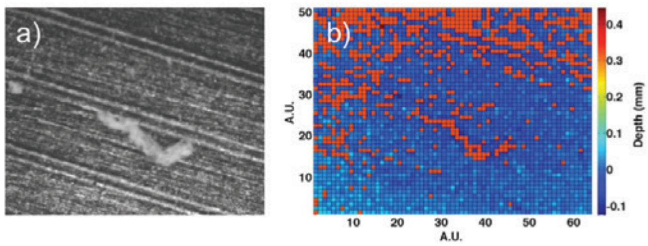


Fig 5 - A) In focus optical image, and b) highly segmented stack after focus find. Certain features from the optical image can be seen in B), but the highly segmented image suffers from increased noise

A control algorithm has also been developed to determine the focus and tilt of the processing beam. It should be noted that the previous algorithm may be used for the same purpose with an additional calibration factor but would not be as accurate as direct analysis of the processing itself. For this code, a pattern of rings are machining into a material. The ring shape was chosen due to pre-existing algorithms that are commonly used to identify circles in images. These algorithms are applied, giving the user an indication of the changes in radius. Figures 6 and 7

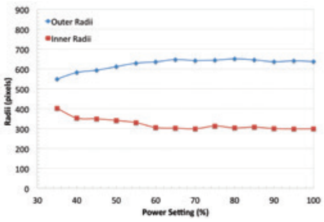


Fig 6 - Change in radii as a function of power setting with processing beam at the focus

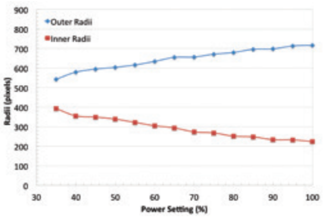


Fig 7 - Change in radii as a function of power setting with processing beam 50 µm away from focus

show the changing radius as a function of laser power setting. It can be seen that the off-focus processing leads to a greater increase in radii with increasing power.

A specific machining pattern will also be used to help determine focus. This can be seen in Figures 8 and 9 (theoretical and experimental respectively) and will be used in conjunction with the radii information. Finally, a tilt control can be done by altering the direction of the machining pattern and looking for a difference in where the threshold is.

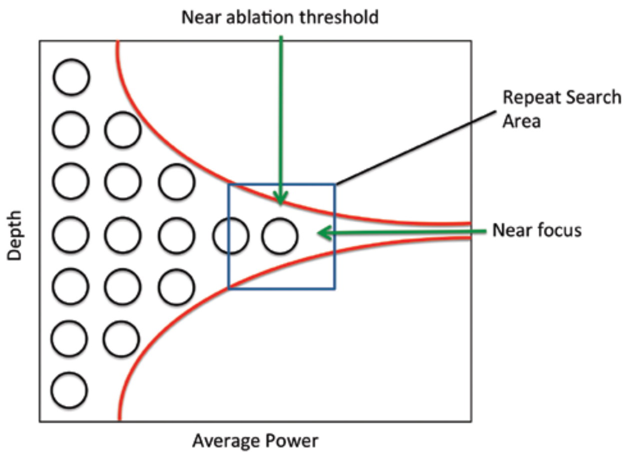


Fig 8 - Proposed machining pattern for processing focus find

The imaging systems will be developed in parallel over the course of the next 6 months. The OCT system design will be finalized and purchased. The system will be attached onto existing processing platforms to enable testing of feedback, specifically monitoring hole depth in blind drilling. An improved optical microscope will also be purchased to allow for improved accuracy in the focus find and tilt control when used in everyday operation. Finally, the DHM prototype testing should be concluded with the next iteration of the prototype designed.

For the control algorithm, the completed code will be added to the user interface to allow for beta testing. Tilt control on processing data will be the next sub control to be developed for the overall system and will be followed by more complex image recognition.

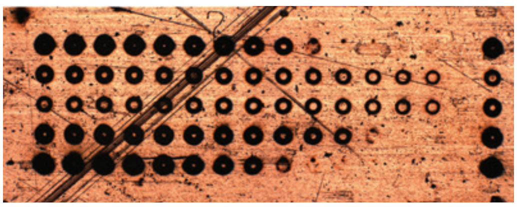


Fig 9 - Processing focus find pattern done on copper sample

Ultra Precision Fabrication of Fused Silica Devices by Femtosecond Laser Irradiation and Chemical Etching (FLICE)

Wenhe Feng

Sponsor: **Amplitude Systèmes**

Femtosecond laser irradiation followed by chemical etching (FLICE) is a novel micro-fabrication technique that allows versatile production of 3D hollow structures consists of two processing steps (Figure 1). Ultrafast laser irradiation is capable of substantially increasing the chemical activity of fused silica glass at a scale of micrometres. Fabrication of 3D hollow structures can be realised by applying a wet etching process after their geometries being defined by the laser scribing within the glass bulk. Compared with techniques such as direct laser ablation, e-beam lithography or focused ion beam micromachining, this technique gives the capability for rapid interior micromachining of glass substrates without requirements for clean room or post-processing. Functional devices such as microfluidic reactors, micro-lens arrays and micro-actuators have already been made in laboratories for the proof of concept.

Our work has shown that KOH water solution is an effective etchant compared with conventional HF etchant. It attacks only modified glass under a sufficiently low temperature, and as a result the etched tunnels' aspect ratio is advantageous over those treated with HF. Raw glass removal rate is comparable to HF under a higher temperature so that rapid removal is achievable. Bubbles generated during the chemical reaction disrupt the resistant layer at the glass-KOH interface in a thin tunnel.

KOH is significantly less toxic than HF. However, innovations are yet to be brought to boost this technique to commercialisation. The mechanisms of laser modification and the enhanced etch rate using alkaline etchants are controversial; the static etch process may limit the maximum achievable structure dimension as well the production throughput; a computational tool useful for the fabrication of such devices with a µm-level precision has not been developed yet.

The focus of this project is to clarify the etch mechanism, to improve the etching speed, and to develop a process involving quantitative description of the etching process allowing an arbitrary shape to be fabricated with optimised precision. At the end of the research programme a novel FLICE technique offering an advantageous and environmental friendly fabrication for microfluidic lab-on-chip devices shall be proposed in order to pave the way for an industrial manufacturing process.

Continued overleaf

Femtosecond laser pulses have high peak power that is capable of inducing optical breakdown in fused silica. An optical breakdown model was set up based on non-linear ionisation rate equations, lectron density evolution and beam propagation. The simulation was used for estimating the laser modified volume with user defined laser parameters and focusing condition as input (Figure 2).

Using the Hurricane *i* laser, a laser processing window was characterised with pulse energy from 1.08 to 3.60 μJ and linear translation speed from 0.1 to 1.5 mm/s at a fixed repetition rate of 5 kHz. The etching temperature was set to 80 °C and the sample was rinsed, dried and measured hourly. Figure 3 (a) and (b) illustrate an image of tunnels and tunnel lengths after etching for 4 hours respectively. Among the pulse energy and speed settings, (2.52 μJ, 0.75 mm/s) was considered optimal as it balances etch rate, etch repeatability and avoidance of undesired damage. The enhanced etch rate of photo-modified SiO_2 under this condition was 200 μm/h, guaranteeing a selectivity of 450:1 given that the etch rate of raw SiO_2 is 0.44 μm/h. The conical shape that comes along with HF etching is hence significantly reduced by using KOH and a tunnel aspect ratio of 75:1 was achieved. Even longer tunnels were fabricated by stacking single tunnels and a length of 11mm was achieved (Figure 3 (c)).

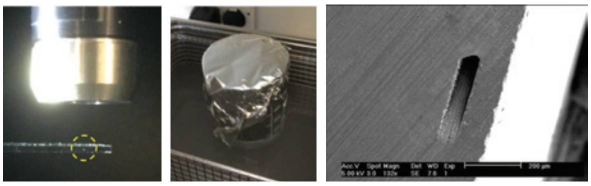
Using the Satsuma laser, six groups of lines were written with 3.4 μJ and 1.0 mm/s at 125 kHz. Each group consisted of 5 lines separated by 5-30 μm. Surface channels (Figure 4 (a)) about 100 μm deep across the 10 mm long glass plate were etched with KOH solution at 120 °C for 220 min. It was observed that the plate thinned by 70 μm, suggesting an etch rate of raw glass of 9.5 μm/h which is comparable to that of HF. An average bottom surface roughness Ra= (5.68 ± 0.59) μm was obtained using a white light interferometer. As a demonstration an Institute for Manufacturing logo (Figure 4 (b)) was also made by firstly layering contours at a step of 90 μm, then etched for 2 hours under 120 °C to expose the pattern, plus another 40 hours under 80 °C to avoid undesired etching of raw material.

From these results we conclude that fused silica processed with Hurricane *i* obtained a considerably selective etchability to permit the formation of tunnels via etching with KOH solution at 80 °C. Meanwhile, fused silica processed with Satsuma was not sufficiently active to allow etching in horizontal plane. The etching selectivity in this case was merely several to one but still sufficient to allow the formation of channels. The etching of photo-modified volume happened in vertical direction after the unmodified fused silica above it was rapidly etched away using 120 °C KOH solution. As a conclusion, requirement for etching selectivity (450:1) or raw glass removal rate (9.5 μm/h) may be fulfilled by different laser parameters and controlling the etching temperature at 80 and 120 °C, suggesting the feasibility of an effective and HF-free FLICE process.

Bibliography

Feng, W. Shevchenko, R., Sparkes, M. R. and O'Neill, W. Precision Glass Microstructure Fabrication Using Ultrafast Laser Induced Chemical Etching, Proceedings of the 14th eu**spen** International Conference 2014 (submitted).

Fig 1 - Steps of FLICE technique.



Irradiation Etching Structures

Table 1 - Parameters of laser systems used in our experiments

	Laser model	
	Spectra-physics Hurricane *i*	Amplitude Systèmes Satsuma
Wavelength	800nm	1030nm
Duration	130 fs	280 fs
Repetition rate	1-5 kHz	1-2000 kHz
Beam ø	5 mm	2.2 mm
M^2 factor	2	1.1

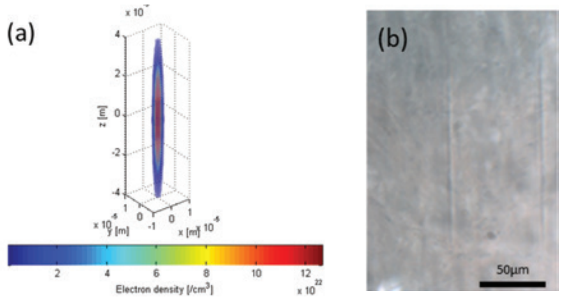


Fig 2 - Simulation and experimentation of optical breakdown in fused silica irradiated using 1030 nm, 280 fs, 125 kHz, 3.4 μJ laser pulses focused with objective f=12.7 mm. (a) Simulated electron density, displayed boundary $1\times10^{15}/cm^3$. (b) Side view image of the laser affect zones.

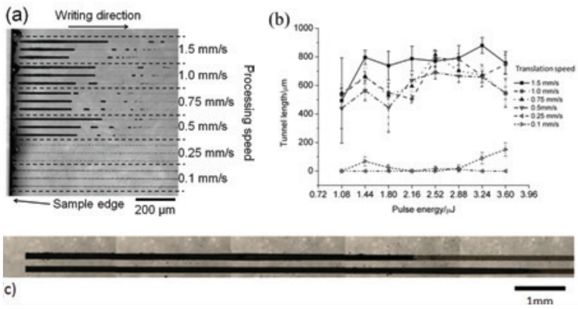
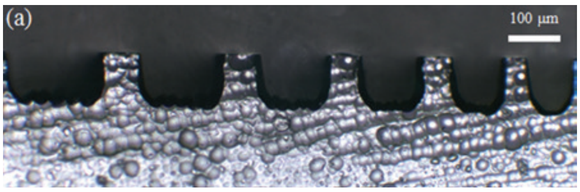


Fig 3 - (a) An overhead view of tunnels in groups of three processed with 2.52 μJ pulses. Transparent zones along tunnels contained residual rinsing water. (b) Tunnel lengths subject to pulse energy and writing speed. (c) High aspect-ratio blind tunnels ~11mm long, breaking a previous record of through tunnels as long as 9.2mm.



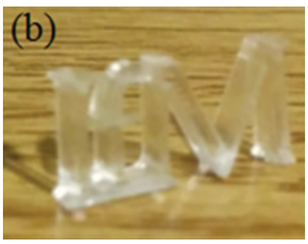


Fig 4 - (a) A side view of the channels' profile after etching. (b) A glass logo of Institute for Manufacturing (9.8×4.8×1.8 mm³) fabricated with FLICE. technique.

Microwave Plasma Technologies for Advanced Surface Fabrication

Susanne Cumberland

Sponsor: **Gooch & Housego**

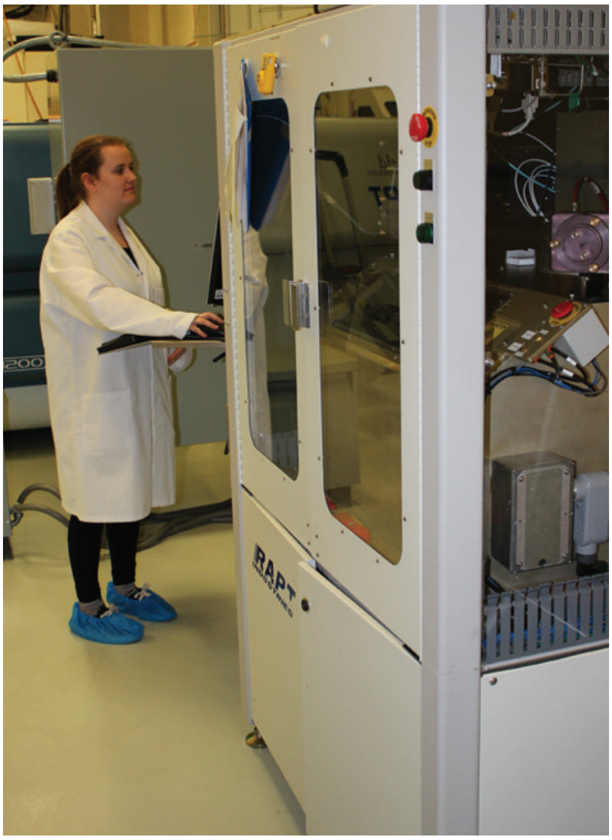
The aim of this project is to increase the processing capability of energy beams that are based on plasma-assisted chemical etching technology. This will be achieved through the creation of a novel microwave generated plasma torch. This research will enable surface correction at nanometre level of silicon-based components. This project will also advance the state-of-the-art optical fabrication techniques used for acoustic-optical devices (AOD) and precision optical systems.

This PhD project has been running for 6 months. During this time initial experimental investigations were centred on the chemical processes occurring using the radio-frequency (RF) generated plasma torch of the RAP300 machine, which is available in the Precision Engineering Institute. This experimental work has developed the technical and scientific knowledge of the PhD candidate. Furthermore, this task has been combined with theoretical research to understand the chemical processes that take place when etching silicon based substrates using SF6 as a reactive gas.

Additionally, a literature review of current microwave generated plasma technologies has been undertaken. The topics included into this literature review are:

- The current design and applications of microwave generated plasma torches
- The differences between RF and microwave generated plasma
- The advantages of microwave generated plasma over RF

The analysis of existing industrial microwave plasma torches will aid with the design aspect of this project. The field of interest is now focused on coaxial microwave generated plasma torches. It is expected that a novel microwave generated plasma torch will be created. Also this dedicated design will allow etching few millimetres wide near-Gaussian trenches at atmospheric pressure.

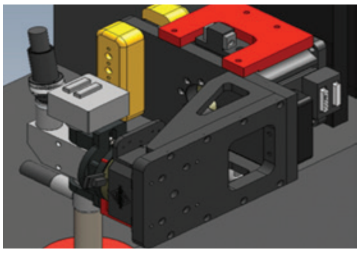


Furthermore, diagnostic methods for the characterisation of the plasma jet have been investigated and researched to find out a suitable non-intrusive one. It is suggested that Optical Emission Spectroscopy (OES) is a promising method for this research work. This plasma diagnostic method shall provide meaningful information about the radical species flux and particle density value.

These two review tasks are the foundation of further design and experimental works for the novel microwave plasma torch.

Design of an Ultra-Precision Laser Machining Platform

George Meakin, Jason Ten and Matthew Pryn



Positioning systems

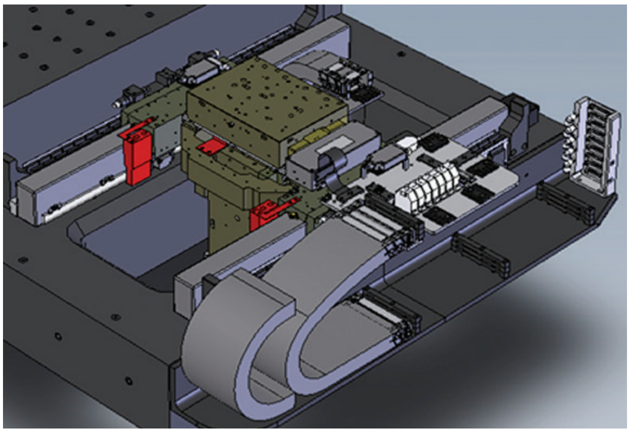
The goal of this three person group project was to design an ultra precision laser machining platform suitable for integration with a FIB system, as part of the Centre's Nano FIB platform. The laser system should be able to add or remove material (resolution 200 nm) from a sample wafer (50mm in diameter), so that FIB machining can be used to finish the process with high accuracy (resolution of 30 nm). Because a laser can remove material far faster than an FIB, relatively large structures can be completed with near FIB accuracy

Continued overleaf

using this method, in a fraction of the time for only using the FIB.

The laser platform should also be suitable for research into laser machining, and for microstructure and MEMS development. Laser positioning accuracy is a major focus for this machine. Commercially available laser machining platforms have a larger working volume and relatively poor accuracy, making them unsuitable for ultra precision application. Because of the diverse potential uses of this technology, the platform required a large degree of flexibility, with multiple lasers and optical setup options made available to user. The user must also have the ability to quickly and easily set-up and calibrate the desired configurations.

The outcome of the project saw the students deliver full design solutions for the laser machining station that placed it ahead of any commercial laser machining station in terms of positioning accuracy, control, and features. The use of in-process metrology was specified, and both an optical coherence tomographic system and a multi-wavelength holographic system were chosen as the main in-process inspection technologies. Fully automated mirror mounts and laser beam positioning will enable the device to be quickly and precisely reconfigured for each process configurations



Positioning systems

and process operation. These options include single spot laser machining; array based laser machining using re-programmable holographic projectors and high speed laser scanning systems utilising electro optic modulators. Three laser source technologies operating at ns, ps and fs timescales were chosen for the processing station and full error mapping and reporting were performed in order to fully specify the system and its overall production capabilities. The technology and system components are now in the procurement/development phase, and the unit is set to be completed by October 2014.

Watch it Made™

Florian Caroff, Armand Didier, Wei-Ting Hsu, Charles Langlais, Gabriel Meng and Tian Tan

The Centre's Educational Demonstrator Programme Watch it Made™ is aimed at enthusing young people into engineering. This group project based at Cranfield, researched watch designs and appropriate production technologies that would allow 12 year old children to produce their own high quality watch, achieved using modern manufacturing technologies.

The aim of the project was to define the designs of watches and machine technologies to enable and enthuse 12 year old children to be proud of making a quality precision engineering product, a quality watch, in a retail environment.

A literature review about watch technology and manufacturing brought the fundamental knowledge to start this project. Business aspects were carried out with market research and surveys. Dealing with children was approached by several meetings and adapted tools.

The project led to the design of a watch combining appealing design and high precision manufacturing technologies. Several prototypes were produced, demonstrating the efficiency of the developed manufacturing process. A business plan was built to turn this experience into a real business. It went through several diverse steps such as market research, customer experience investigations, health and safety issues and sales forecasts.

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

Nan Yu

This PhD project is about design, fabrication, and characterisation of novel nozzles for Inductively Couple Plasma (ICP) torches. These nozzles will enable the creation of highly collimated plasma jets used for the deterministic removal of silicon based material. Here in this project, the footprint of plasma jet is targeted in the range of 3-10 millimetres in diameter. These dedicated plasma jets will be used through a dwell time method for the correction of optical surfaces and rapid removal of mid-spatial frequencies (MSF) on metre class optics (Figure 1).

The research project fits into core activities of the EPSRC Centre for Innovative Manufacturing in Ultra Precision. Among other activities, this Centre develops advanced fabrication processes for mass production of ultra-precise metre size optics. The final step of the optical fabrication chain - grinding, lapping, polishing, and figuring- is known to be time consuming. For the purpose of this research work, the processing time is set to be less than 10 hours per square metre. Consequently there is an emphasis on increasing the material removal rate compared with state-of-the-art energy beam technology.

In the past six months, a novel nozzle design of plasma torch has been investigated based on both CFD simulation and experiments. Thus CFD results and experimental work enable correlation between nozzle dimensions and the material removal footprint of plasma jets. Overall, this investigation aims to determine design rules for plasma jet nozzles.

Indeed, novel numerical models of two existing De-Laval nozzles were created using FLUENT. The initial conditions of this study include velocity, temperature and pressure distribution in the torch nozzle. Thus the plasma jet velocity distributions both through the nozzle and onto the substrate surface are analyzed. Figure 2 shows an initial result of the simulation carried out. This investigation enables to compare the beam performances of different nozzles. Further comparisons among different nozzle designs will be presented in the future.

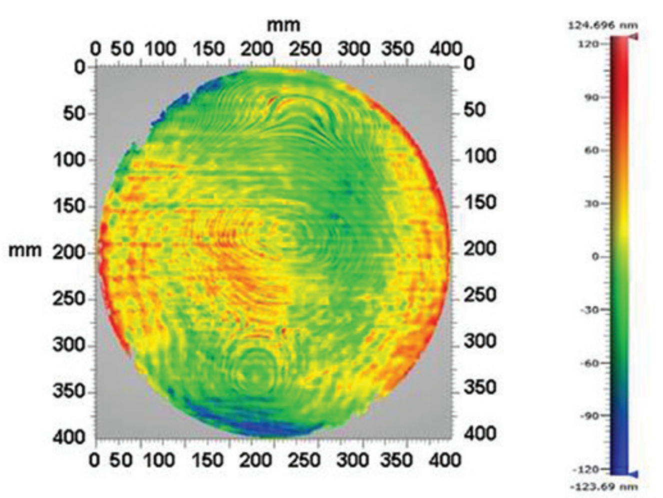


Fig 1 - Surface topography showing the MSF features

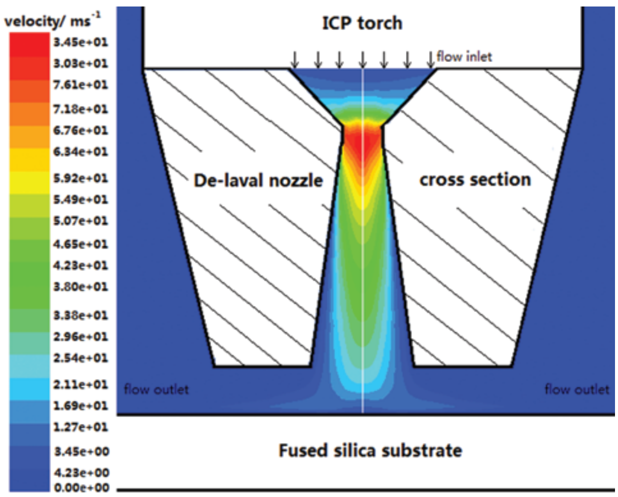


Fig 2 - Velocity distribution of the flow

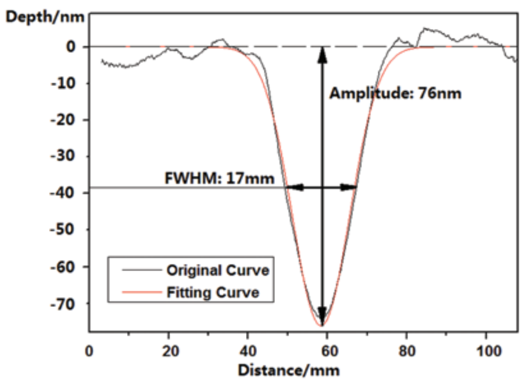
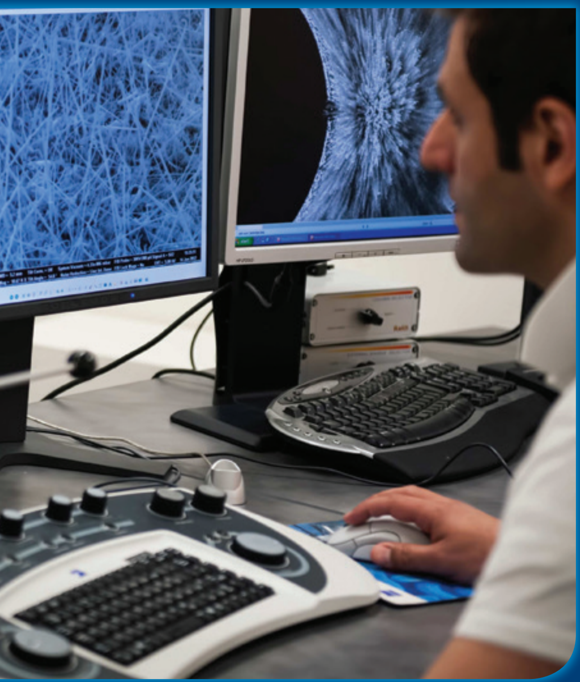


Fig 3 - Fitting curve of the footprint

Also, in order to investigate the relationship between size of plasma jet footprint and material removal rate, footprint experiments were carried out on 200mm x 200mm fused silica substrates. The processed surface was measured using a Twyman–Green interferometer. The profile of the etched footprint was assessed to be near Gaussian, and the Full Width at Half Maximum (FWHM) was determined to be 17mm (Figure 3).

From now on, a set of new nozzles will be fabricated and characterized.

Centre for Doctoral Training in Ultra Precision



An extension to the EPSRC Centre for Doctoral Training in Ultra Precision (CDT-UP) was awarded in March 2014, under grant reference EP/L016567/1. The new award seeks to build upon the creation of the EPSRC Centre for Innovative Manufacturing in Ultra Precision at Cambridge and Cranfield Universities in October 2012.

The current phase of the CDT-UP is completing its second of three funded cohorts, of 24 students in total. We propose to further develop our leading training and research environment that will deliver to industry highly skilled ultra precision engineers 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 second phase of the Centre for Doctoral Training will commence in October 2015 and will consist of 4 cohorts of 10 students. The Centre has a total value of £6.2M and will run until 30th September 2022.

The collaborating team from Cambridge and Cranfield Universities represent a strong ultra precision partnership, which is strengthened in the new Centre with collaborations across the Cambridge Departments of Material Science and Chemistry and the ultra precision laboratories and unique facilities across Cambridge and Cranfield.

Developed as a result of significant EPSRC/HEFCE investments, these facilities provide the CDT-UP an unequalled practical foundation in the training of new researchers/engineers and providing capability for disruptive innovation. It is a proven alliance of highly complementary institutions. The partnership reinforces relationships built in the success of previous co-operations between investigators through EPSRC funded Grand Challenges, IMRC and IKC programmes. New partnering investigators are fully engaged, bringing expertise in emerging product developments. This aspect is recognised as being critical to the direction setting and focus of the EPSRC Centres for Innovative Manufacturing in Ultra Precision, Large Area Electronics, Laser Based Production Systems, and Graphene Engineering. The investigators and the universities place significant priority on high value manufacturing as evidenced through their combined investment in infrastructure and research programmes.

A central aim of the extended Centre is to widen the impact of the research education and training to cover aspects of ultra precision in other disciplines. In order to do this the following group leaders and their research teams have joined us. Professor Andrea Ferrari is Professor of Nanotechnology and Royal Society Wolfson Research Merit Award Holder. He is the Director of the Cambridge Graphene Centre and Head of the Nanomaterials and Spectroscopy Group at the University of Cambridge Engineering Department and Nanoscience Centre. Professor Ferrari will lead the Graphene material and device fabrication activities.

Dr Paul Barker is Senior Lecturer in the Department of Chemistry, Cambridge. His research goal is to engineer novel proteins and polypeptide based assemblies that can be used in molecular electronic devices. His support is central to extending ultra precision activities in self-organisation and bottom-up manufacturing techniques.

Professor Bill Clyne is Professor of Mechanics and Materials in the Department of Materials at Cambridge. His research is focused on the processing and properties of new types of materials and coatings.

Professor Richard Leach is Principal Research Scientist at the National Physical Laboratory, London, a leading expert in advanced surface metrology, and will support the CDT-UP training and research programme in ultra precision metrology.

Dr Chris Rider is Director of the new EPSRC Centre for Innovative Manufacturing in Large Area Electronics and will support the Centre activities in large area electronics manufacturing.

Dr Heather Almond is a Research Fellow in Electrochemistry at Cranfield, and will support the research activities in microsystems manufacturing.

Dr Ronan Dailey is a new academic appointment within the Institute for Manufacturing at Cambridge and will support the teaching and research activities in aspects of bio-engineering.

Dr Michael deVolder is a new academic appointment within the Institute for Manufacturing at Cambridge and will support the teaching and research activities of the CDT-UP in aspects of the production of carbon nanotube devices.

The Cambridge and Cranfield Engineering activities have top rankings for General Engineering and Manufacturing in the latest RAE in 2008, these results place Cambridge and Cranfield as two of the most sought after locations to undertake engineering research at PhD level.

Awards and Prizes

Jake Larsson

One of our PhD students, won the Autocar-Courland Next Generation Award. This award of £7,500 is provided by 6 automotive companies and provides Jake with a 1 month duration work experience session at each company: including both JLR and McLaren.

Professor Paul Shore

Prof Paul Shore, Centre Director, won the Jacob Wallenberg Foundation prize for 2014. This award of £20,000 will be applied to develop air bearing technologies applied to reel to reel processing.

Jon Parkins

A first year PhD student in the Centre for Industrial Photonics, has been awarded the Leete Premium Award from the Worshipful Company of Engineers in support of his PhD studies. The award is newly established for this academic year, and is awarded in support of excellence in production engineering research. The award will support Jon in his research towards development of laser additive manufacturing capability, in particular with application to the biomedical implants industry.

The endowment for the award has been left to the Worshipful Company of Engineers by late Liveryman Dr David Leete, a successful electrical engineer with a long and distinguished career. Dr Leete graduated from King's College London in 1941, and subsequently obtained a PhD from Manchester University. His career involved testing of Mosquito aeroplanes, the development of radar and inventing his own type of Sat Nav. He later established a Consulting Engineering Practice which he ran until he was nearly 90, and was one of the oldest members ever to have joined the Company when he was made a Liveryman in 1993 at the age of 75. He sadly passed away on 12th December 2011, bequeathing a substantial sum to the Company, in order to support the advancement of engineering and education.

Quality and Metrics

	Target	Achieved at Mid-Term point
Publications		
Journal papers 1 paper per 1 research staff person year	55	40
Keynotes given by Centre investigators and researchers 1 keynote given at international conference per 2 staff person years	25	10
Student keynotes /awards 1 student provided keynote or presentation award per 3 staff person years	8	2
Outreach		
Strategic outreach meetings 3 per year to establish Centre as UK hub	15	8
Development		
PhDs completed Directly funded by the Centre	16	N/A
PhDs completed Funded by the CDT in Ultra Precision	30	N/A
Promotion of 40% of staff engaged in UP centre	8	3
40% of PhDs to hold RA, engineer or science positions in UK	12	N/A
Partnerships		
Maintain original partners 75% still active after 5 years	3	3
Engage new industrial partners 2 per year	10	6
Uptake		
Centre main project taken forward by industry	3	1
Centre		
Planning and delivery Hold overall programme by delivering Gantt deliverables and milestones	22	9
Added value to Centre Secure additional funding equal to EPSRC original funding	£6.8m	>£7m

Centre Publications

Journal Publications

Burt, D. P., Dobson, P. S., Docherty, K. E., Jones, C. W., Leach, R. K., Thoms, S., Weaver, J. M. R. and Zhang, Y. (2012) - "Aperiodic interferometer for six degree of freedom position measurement"

Optics Letters, 37, 1247-1249.

Chen, J-S., Chu, D. and Smithwick, Q. (2014) - "Rapid hologram generation utilizing layer-based approach and graphic rendering for realistic three-dimensional image reconstruction by angular tiling"

Journal of Electronic Imaging, 23(2), 023016.

Claverley, J. D., Leach, R. K. (2013) - "Development of a three-dimensional vibrating tactile probe for miniature CMMs"

Precision Engineering, 37, 491-499.

Comley, P., Morantz, P., Shore, P. and Tonnellier, X. (2011) - "Grinding metre scale mirror segments for the E-ELT ground based telescope"

CIRP Annals Manufacturing Technology, 60(1), 379-382.

Coupland, J. M., Mandal, R., Polodhi, K. and Leach, R. K. (2013) - "Coherence scanning interferometry: linear theory of surface measurement"

Applied Optics, 52, 3662-3670.

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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de Podesta, M., Sutton, G., Underwood, R., Davidson, S. and Morantz, P. (2011) - "Assessment of uncertainty in the determination of the Boltzmann constant by an acoustic technique"

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Earl, C., Hilton, P. and O'Neill, W. (2012) - "Parameter influence on surfi-sculpt processing efficiency"

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Journal of Materials Research, 29(3), 392-402.

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Journal of Microscopy, 251, 99-107.

Foreman. M. R., Giusca, C. L., Coupland, J. M., Török, P. and Leach, R. K. (2013) - "Determination of the transfer function for optical surface topography measuring instruments – a review"

Measurement Science and Technology, 24, 052001.

Giusca, C., Leach, R. K. and Forbes, A. B. (2011) - "A virtual machine based uncertainty for a traceable areal surface texture measuring instrument"

Measurement, 44, 988-993.

Giusca, C. L., Leach, R. K., Helery, F., Gutauskas, T. and Nimishakavi, L. (2012) - "Calibration of the scales of areal surface topography measuring instruments: Part 1 - Measurement noise and residual flatness"

Measurement Science and Technology, 23, 035008.

Giusca, C. L., Leach, R. K. and Helery, F. (2012) - "Calibration of the scales of areal surface topography measuring instruments: Part 2 – Amplification coefficient, linearity and squareness"

Measurement Science and Technology, 23, 065005.

Giusca, R. K. and Leach, R. K. (2013) - "Calibration of the scales of areal surface topography measuring instruments: Part 3 – Resolution"

Measurement Science and Technology, 24, 105010.

Goel, S., Luo, X., Comley, P., Reuben, R.L. and Cox, A. (2013) - "Brittle-ductile transition during diamond turning of single crystal silicon carbide"

International Journal of Machine Tools and Manufacture, 65, 15-21.

Habibi, S., Sparkes, M., Langford, R. M. and O'Neill, W. (2013) - "Surface and substrate effects of ultraprecise fabrication with FIB on HOPG characterized by Kelvin probe force microscopy"

Submitted to the Journal of Vacuum Science and Technology A, paper number JVSTA-L-13-307.

Hallam, T., Cole, M. T., Milne, W.I. and Duesberg, G. S. (2014) - "Field emission characteristics of contact printed graphene fins"

Small,10, 95-99.

Henning, A. J., Giusca, C. L., Forbes, A. B., Smith, I. M., Leach, R. K., Coupland, J. M. and Mandal, R. (2013) - "Correction for lateral distortion in coherence scanning interferometry"

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Jiang, D. Xu, H. Pivnenko, M. Chu, D. (2014) - "Compact phase shifter based on highly anisotropic liquid crystals for microwave frequency"

Electronics Letters, 50, 525-526.

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Nanotechnology, 22, 062001.

Leach, R. K., Claverley, J., Giusca, C. L., Jones, C., Nimishakavi, L., Sun, W., Tedaldi, M. and Yacoot, A. (2012) - "Advances in engineering nanometrology at the National Physical Laboratory"

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Leach, R. K. and Sherlock, B. (2014) - "Applications of super-resolution imaging in the field of surface topography measurement"

Surface Topography: Merology and Properties, 2, 123001.

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Light: Science and Applications, 1

Lupoi, R., Sparkes, M., Cockburn, A. and O'Neill, W. (2011) - "High speed titanium coatings by supersonic laser deposition"

Materials Letters, 65, 3205-3207.

Mandal, R., Coupland, J. M., Leach, R. K. and Mansfield, D. (2014) - "Coherence scanning interferometry: measurement and correction of 3D transfer and point-spread characteristics"

Applied Optics, 53, 1554-1563.

Meyer, P., Claverley, J. and Leach, R. K. (2012) - "Quality control for deep x-ray lithography (LIGA): a preliminary metrology study"

Microsystem Technologies, 18, 415-421.

Nedic, S., Tea Chun, Y., Hong, W-K., Chu, D. and Welland, M. (2014) - "High performance non-volatile ferroelectric copolymer memory based on a ZnO nanowire transistor fabricated on a transparent substrate"

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Rangesh, A. and O'Neill, W. (2012) - "The foundations of a new approach to additive manufacturing: Characteristics of free space metal deposition"

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Shore, P. and Morantz, P. (2012) - "Ultra-precision: enabling our future"

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Underwood, R. Davidson, S., Perkin, M., Morantz, P., Sutton, G. and de Podesta, M. (2012) - "Pyknometric volume measurement of a quasispherical resonator"

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Journal of Materials Chemistry, 22, 14-718.

Conference Publications

Chesna, J. W., Schimuzu, Y. and Leach, R. K. (2013) - "On the use of mercury sessile drops as reference artefacts for the calibration of optical surface topography measuring instruments"

Proceedings of the 28th Annual Meeting of ASPE, St Paul, USA, 20-25 October 2013, 74-77.

Cockburn, A., Lupoi, R., Sparkes, M. and O'Neill, W. (2012) - "Supersonic laser deposition of corrosion and wear resistant materials"

Proceedings of the 37th International MATADOR 2012 Conference, 25-27 July 2012, Manchester, UK, 387-391.

Cockburn, A., Sparkes, M., Lupoi, R., Luo, F. and O'Neill, W. (2013) - "Deposition of Stellite® and Inconel Coatings using Supersonic Laser Deposition"

The International Laser Applications Symposium 2013, 12-13 March 2013, Nottingham, UK.

Earl, C., Hilton, P., Blackburn, J. and O'Neill, W. (2011) - "A comparitive study of 3D laser surface modification and the Humping Phenomenon"

30th International Congress on Applications of Lasers and Electro-Optics (ICALEO 2011), 23-27 October 2011, Orlando, FL, USA, 442-450.

Hopkinson, D., Cockburn, A. and O'Neill, W. (2011) - "Fiber laser processing of amorphous rare earth NeFeB magnetic materials"

30th International Congress on Applications of Lasers and Electro-Optics (ICALEO 2011, 23-27 October 2011, Orlando, FL, USA, 1233-1240.

Leach, R. K., Jones, C. J., Sherlock, B. and Krysinski, A. (2013) - "The high dynamic range surface metrology challenge"

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Morantz, P. (2012) - "Multi-process strategy for freeformoptics manufacture"

3rd International Conference on Nano Manufacturing (nanoMan2012), 25-27 July 2012, Tokyo, Japan.

Morantz, P., Comley, P., Tonnellier, X. and Shore, P. (2011) - "Precision free-form grinding of metre-scale optics"

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Pangovski, K., Li, K. and O'Neill, W. (2011) - "Investigation of low nanosecond light-matter interaction mechanisms"

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Pangovski, K. and O'Neill, W (2011) - "Silicon response study to 1000 ns - 1 ns single pulses"

Ultra Precision Laser Manufacturing Systems, Technologies and Applications, 13 September 2011, Cambridge UK.

Pangovski, K., Li, K. and O'Neill, W. (2011) - "Application of picosecond lasers for surface modification and polishing"

Photonics London 2011, 8 September 2011, London, UK.

Pangovski, K., The, P. S., Alam, S., Richardson, D., Demi, A. G. and O'Neill, W. (2012) - "Designer pulses for precise machining of silicon – a step towards photonic compositions"

31st International Congress on Applications of Lasers and Optics-Electronics (ICALEO 2012), 23-27 September 2012, Anaheim, CA, USA.

Pangovski, K., Sparkes, M., Cockburn, A. and O'Neill, W. (2013) - "Digital holograph analysis of laser induced micro plasma in micro machining applications: temporal and spatial comparisons to thermo nuclear explosions"

Presented abstract at the 2nd Annual EPSRC Manufacturing the Future Conference, 17-18 September 2013, Cranfield, UK. This presentation won the CIRP sponsored best presentation award.

Pangovski, K., Sparkes, M., Cockburn, A. and O'Neill, W. (2013) - "Resource efficiency improvements through laser processing of designer materials"

European Conference on Lasers and Electro-Optics 2012 (CLEO Europe), 12-16 May 2013, Munich, Germany.

Parkins, J., Jourdain, R., Marson, S., Shore, P., Sparkes, M. and O'Neill, W. (2012) - " Laser Assisted Plasma Processing: An Overview"

Proceedings of the 12th International Conference of the European Society for Precision Engineering and Nanotechnology, 4-8 June 2012, Stockholm, Sweden, 364-367.

Sheu, D-Y., Claverley, J. D. and Leach, R. K. (2014) - "Testing the mechanical characteristics and contacting behavior of novel manufactured and assembled sphere-tipped styli for micro-CMM probes"

Proceedings of the 7th International Precision Assembly Seminar (IPAS), 16-18 February 2014, Chamonix, France, 13-19.

Shore, P., Morantz, P., Read, R., Carlisle, K., Comley, P. and Castelli, M. (2013) - "Design overview of the µ4 compact 6 axes ultra precision diamond machining centre"

Laser Metrology and Machine Performance X, Proceedings of the 10th International Conference and Exhibition on Laser Metrology, Machine Tool, CMM and Robotic Performance (Lamdamap 2013), 20-21 March 2013, Buckinghamshire, UK, 9-19.

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Xu, H., Davey, A. B., Crossland, W. A. and Chu, D. P. (2012) - "UV durable colour pigment doped SmA liquid crystal composites for outdoor trans-reflective bi-stable displays"

Proceedings of SPIE 8475, Liquid Crystals XVI, 12-13 and 15 August 2012, San Diego, CA, USA, 847506-8.

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Pangovski, K. and O'Neill, W. (2012) - "Designer Laser pulses for materials processing"

The Laser User, 67, p26-28.

Appendices

Steering Group

Dr Paul Atherton (Chairman) Nanoventures

Dr Karen Brakspear EPSRC

Prof Daping Chu University of Cambridge

Prof Chris Evans University of North Carolina at Charlotte

Chris Rider University of Cambridge

Prof Richard Hague University of Nottingham

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Andy Sellars Technology Strategy Board

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ALE Ltd

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CERN

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Gooch & Housego PLC

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Hexagon Metrology Ltd

IPG Photonics

Michell Instruments

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Loxham Precision

Microsharp Corporation Ltd

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NSK Ltd

Oxford Instruments

Plarion Ltd

Plasma Quest Limited

Poeton Ltd

Qioptiq

Renishaw

Riken

Sphere Medical Limited

SPI Lasers

Technology Strategy Board

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University of North Carolina at Charlotte

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