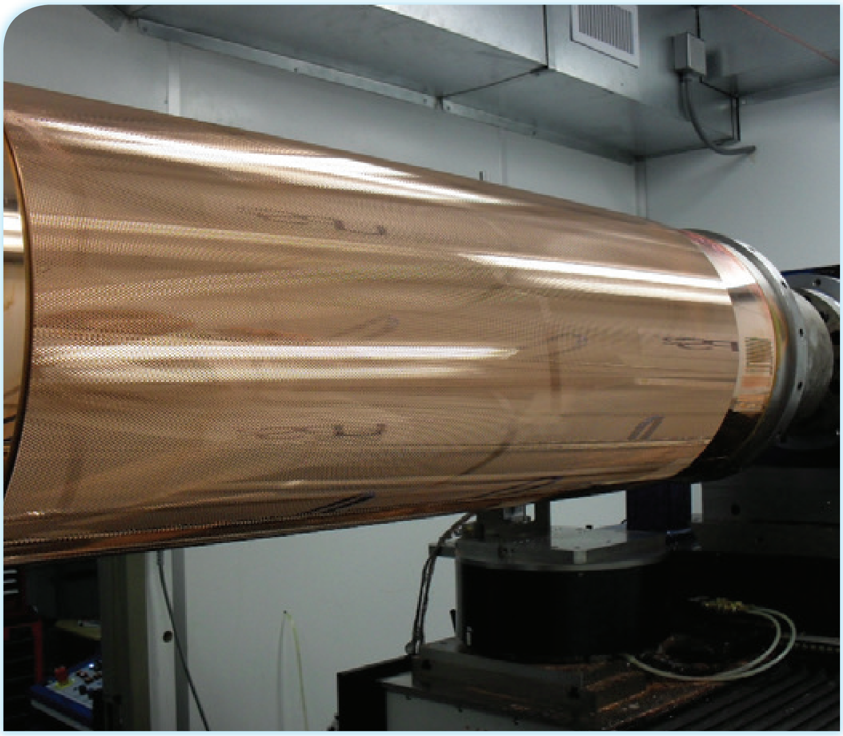
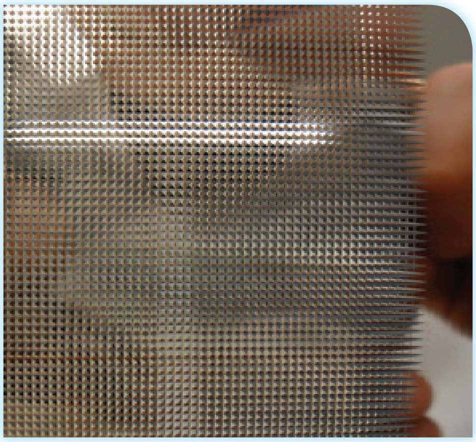
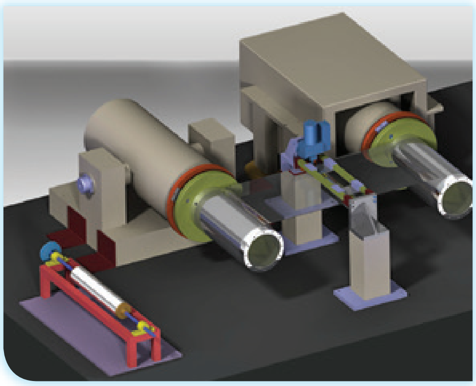
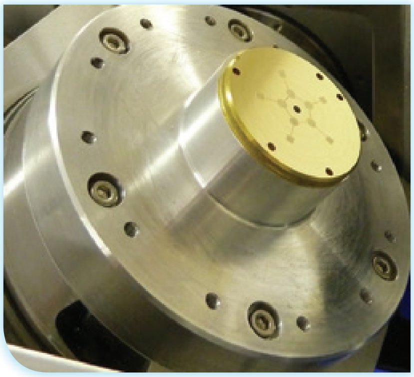
EPSRC Centre for innovative manufacturing in ultra precision

EPSRC
Pioneering research and skills





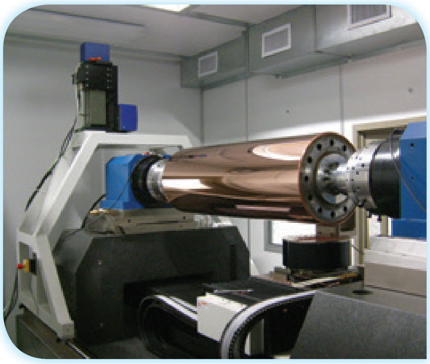




Annual Report

2012/13

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, eu**spen** Limited and to Fusing Creativity Ltd. for the design of this report and John Pullin for his assistance with content.

Executive Summary

This second year report provides an overview of the activities of the EPSRC Centre for Innovative Manufacturing in Ultra Precision providing an indication of progress that has been made thus far.

The goal of the Centre is to better position the UK to secure wealth creation from manufacturing products stemming from inventions in key emerging markets.

To achieve this goal we are undertaking early stage production research to establish the new processing technologies demanded for effective production of emerging products. Our technical focus is on realising research platforms and capable processes that can define a new generation of rapid and effective ultra precision production systems.

We aim to reconcile the simultaneous demands of:

- nanometre scale/accuracy 3D feature creation
- multi-material processing
- rapid production capacity and
- overall scale

Our Centre is establishing advanced manufacturing technologies that are pivotal to important emerging products. Through a close interaction with the UK precision manufacturing supply chain, the UK's emerging product developers and leading international organisations, our Centre is establishing a unique world-leading UK-based ultra precision research centre.

The Centre is leading a number of production research activities. These include the design and build of our own highly functional production research platforms; research into new processing techniques; and the development of greater awareness throughout the UK's precision production engineering research community.

To facilitate realisation of the Centre's wider objectives we are training a new generation of ultra precision researchers through an aligned Centre for Doctoral Training. And for the longer term, through the creation of 'educational demonstrators', we will bring some of the fascination of modern precision engineering into school classrooms. We intend to place knowledge and appreciation of this exciting branch of manufacturing in the hands and minds of UK children and to foster a 'can-do mentality' ahead of their selection of subjects for further study and later careers.

Paul Shore
Centre Director

National Strategy Programme Development

Ambition

The EPSRC Centre in Ultra Precision is developing a National Strategy Programme. Its ambition is the creation of a thriving community that networks across academia and industry with the purpose of maximising opportunities stemming from the latest ultra precision technologies.

This National Strategy Programme is currently in its formation phase. It is drawing together a community from the UK's ultra precision capacity covering its people, facilities and new ideas. It is working together with organisations that aim to stimulate the UK's prowess in the engineering manufacturing arena.

This UK community is being developed with supportive information services that can facilitate new collaborations. These pave the way to a necessary long-term momentum that will yield UK wealth creation from its leading research outputs and capabilities in ultra precision.

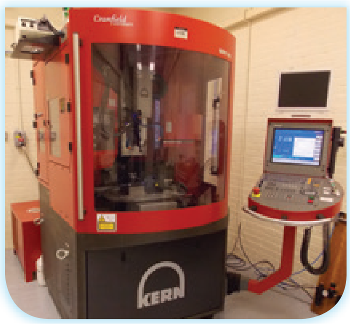
A key strategy programme output will be to create a self-supporting network, operating at many levels, on a UK national basis. We expect this UK network to have a similar basis to that seen within the European Society of Precision Engineering and Nanotechnology www.euspen.eu, which is headquartered at Cranfield.

Objectives and Mechanisms

Ultimately, the Ultra Precision Network will become widely influential and receive recognition in regards to its impact on: economic contributions, national awareness, young people engagement, international research standing, societal benefits and long term vision for growth of UK manufacturing in global terms.

The key elements of the National Strategy Programme include:

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



National Strategy Programme Team

The Centre welcomed two new members of staff to its team in 2013.

Martin O'Hara joined the team in October 2013 as the National Strategy Manager. Martin oversees the development and implementation of the National Strategy Programme, which aims to establish the Centre as the EPSRC national hub in ultra precision engineering and to promote public awareness of the Centre. He has spent more than 20 years in industry implementing new product and process introductions and development, and is looking to use this experience to help industry and academia bridge the gap from research to industrial application for different ultra precision technologies and helping to build a cohesive UK ultra precision community.

Enza Giaracuni joined in February 2013 as Centre Co-ordinator. As an existing member of staff at Cranfield University, she has experience of working in a materials science and engineering research and teaching environment and was involved in the administration of a previous EPSRC funded Innovative Manufacturing Research Centre led by the University. Enza also worked for eu**spen**, the European Society for Precision Engineering and Nanotechnology, when its headquarters were first established in 1999 at Cranfield University. eu**spen** was created through funding under an FP4 EU project initiated by Cranfield Professors Pat McKeown and John Corbett together with other leading Professors at Fraunhofer Institutes in Germany. Today eu**spen** is a fully independent company, registered as a charity in the UK, but operating across Europe with more than 600 members.

Enza co-ordinates the Centre's National Strategy Programme activities which include industrial and academic research specific networking events, industrial short courses, marketing material, website maintenance and the development of the UK database of ultra precision equipment and facilities. Enza also facilitates the Centre's attendance at national and international conferences and exhibitions.

Website and UK Database of Ultra Precision Facilities and Equipment

The Centre's website **www.ultraprecision.org** was launched in May 2013. The site was professionally designed and developed by a local company which also designed the Centre's branding. The website provides information on the importance of ultra precision technologies and is the Centre's primary resource for informing the ultra precision community and the general public about its complete spectrum of research activities and the National Strategy Programme, linking into the Centre for Doctoral Training in Ultra Precision led by the University of Cambridge.

The website also advertises technical and networking events that are organised by the Centre as part of its National Strategy Programme of activities. In the future, it is planned that it will include a more detailed programme of worldwide events such as those organised by the European Society of Precision Engineering and Nanotechnology (eu**spen**) and the American Society for Precision Engineering (ASPE) and other EPSRC Centres of relevance. It will also list the national and international events where the Centre will be exhibiting and conferences where Centre members are presenting.

In August 2013, the UK database of ultra precision equipment and facilities was incorporated into the Centre's website. The database is openly available with detailed and up-to-date information on the UK's ultra precision leading laboratories and the equipment housed within them. The utilisation levels of the specialist equipment are listed and access availability for commercial and research purposes is indicated. This activity is in its early stages of development and it is envisaged that the register of entries will increase significantly next year.

The Centre has its own YouTube channel **CranCamUP** and recently set up the **Ultra Precision UK Network Group** on LinkedIn and Twitter account **@UPrecisionUK**.

Industrial Outreach

March 2013

Lamdamap 10th International Conference

Kavli Royal Society International Centre, Buckingham, UK.

This event brought together machine tool manufacturers, measurement and control specialists and engineers to discuss comprehensive developments in instrumentation, technologies and engineering for production of the most advanced products. A tour of the Centre's precision engineering facilities at Cranfield was provided.

March 2013

Innovate UK

London, UK.

The Centre participated in a joint exhibition co-ordinated by the EPSRC Centre in Photonics at this networking event for business, academia and government.

June 2013

Integrated Knowledge Centre in Ultra Precision Structured Surfaces Review Meeting

Royal Academy of Engineering, UK.

Delegates from industry, government and academia heard presentations about the IKC research and development portfolio, on-going facilities and how the establishment of the EPSRC Centre in Ultra Precision and its aligned Doctoral Training Centre in Ultra Precision will continue to support the development of ultra precision expertise in the UK.

July 2013

Renewable Energy Machines, invited lecture by Professor Alexander Slocum

Massachusetts Institute of Technology, USA.

The Centre hosted a lecture in which Alexander Slocum, Pappalardo Professor of Mechanical Engineering at MIT, returned to Cranfield after 25 years with a special lecture on engineering innovations for effective renewable energy. Over 80 staff and students from the School of Applied Sciences and School of Engineering attended.

November 2013

Innovation in Materials

Royal Academy of Engineering, UK.

Prof Bill O'Neill gave a presentation at the latest of the Royal Academy of Engineering's 'Innovation in…' series of events, giving an overview of some of the most recent advances in materials. The event showcased applications that have reached society or are expected to in the next 5-10 years.

October 2013

NewTech 2013

KTH Royal Institute of Technology, Sweden.

Professor Paul Shore presented a keynote lecture at this conference on Advanced Manufacturing Engineering and Technologies highlighting the demands for ultra precision across a wide range of industries and environmental themes.

November 2013

Manufacturing Technology Centre

Coventry, UK.

Prof Bill O'Neill gave a presentation on the use of lasers in development of designer materials for next generation products.

External events – during its second year, the Centre participated in several industrial outreach events.

Our own events

May 2013

National Manufacturing Debate

Cranfield University, UK.

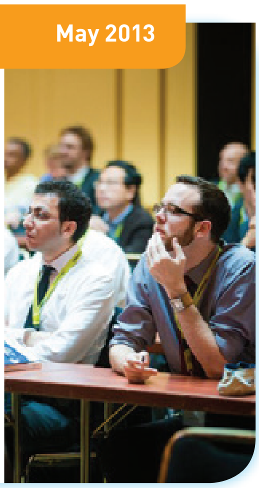
This event brought together manufacturing professionals from many sectors to discuss and debate current challenges in the industry, and to encourage networking and collaboration across sectors for continued and long-term growth.

May 2013

euspen's 13th International Conference

Berlin, Germany.

This conference and exhibition provided a forum for industrialists and academics to review leading industrial innovation, progressive research and technology developments. Professor Paul Shore was eu**spen**'s President from 2011 to 2013, handing over the role during the conference.



September 2013

2nd Annual EPSRC Manufacturing the Future Conference

Cranfield University, UK.

This conference was attended by the EPSRC Centres for Innovative Manufacturing, aiming to exchange best practice and work in progress and communicate the value of the manufacturing research community to stakeholders. This conference is the only one of its kind to focus on the leading edge (TRLs 1-4), taking a broad perspective on manufacturing.

September 2013

11th International Conference on Manufacturing Research (ICMR)

Cranfield University, UK.

This conference is a major event for academics and industrialists engaged in manufacturing research and has been held annually in the UK since the late 1970s. The conference brings together a broad community of researchers who share a common goal; developing and managing the technologies and operations that are key to sustaining the success of manufacturing businesses.

Research Partnerships

The Centre has developed a number of new research partnerships in the past year, most notably the following:

Stryker Howmedica is working with Prof Bill O'Neill to explore the potential of increasing the performance of additive manufacturing technologies for the production of biomedical implants. This research programme started in October 2013.

Michell Instruments is a leading Cambridge-based company which manufactures humidity sensors for a wide range of industrial applications. Prof Tim Wilkinson, an investigator within the Centre, and his team are currently developing a range of fibre-based optical sensors that will extend the operating range of products for Michell Instruments.

Gooch and Housego, a leading supplier of acousto-optical devices is working with Prof Paul Shore and Dr Renaud Jourdain on plasma processing of critical items.

The research conducted within the Centre has the potential to impact research carried out within a number of new EPSRC Centres. The EPSRC Centre in Ultra Precision is developing links across a host of centres including, the EPSRC Centre in Large Area Electronics, Laser Based Production Processes and Graphene Engineering. These Centres will develop numerous emerging products that will be realised through fabrication capabilities that can manipulate multi-material substrates at extreme levels of precision and with 3D feature shape control at the nanometre and micrometre scale. The engagement of these new collaborations will greatly extend and strengthen the impact of the research carried out within the Centre. Links have been formed through Prof Shore being a member of the advisory panel of the EPSRC Centre in Large Area Electronics, whilst Prof O'Neill is directly involved with the EPSRC Centre for Laser Based Production Processes.

Educational Outreach

Precision Engineering laboratory tour for the London International Youth Science Forum

Schools and Young People

Local school **Samuel Whitbread Academy** visited the Centre for a talk on how precision engineering is essential to facilitate emerging technologies. This was followed by a tour of laboratories and demonstrations. The Centre was also represented at the Samuel Whitbread Academy Careers Convention, offering students in years 9-13 the opportunity of talking and discussing their career aspirations.

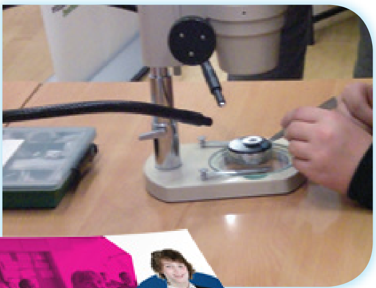
Throughout the year the Centre also hosted several work experience placements for students from local schools studying science and engineering.

The EPSRC Centre in Ultra Precision hosted the **London International Youth Science Forum** in July 2013. The Forum attracts over 350 of the world's leading young scientists aged 17-21 who are either currently studying or applying for undergraduate education from more than 50 participating countries including New Zealand, India, Jamaica and Brazil. There is an active social calendar with events designed to enable those from around the world to learn about different cultures. The scope of the Forum extends further than broadening scientific understanding to engage students in education on other cultures and develop lasting, international friendships. 27 students attending this annual two-week residential event at Imperial College London visited the Centre as part of the 2013 programme. The students were also introduced to Cranfield's research activities in science, technology and engineering.

Cambridge Science Festival 2013

In March 2013, the Institute for Manufacturing welcomed over 1000 visitors as part of the annual **Cambridge Science Festival**. In addition to talks, laboratory tours, exhibitions and displays, visitors could partake in various practical scientific activities guaranteed to amaze and delight both young and old.

In July 2013 a presentation about ultra precision laser material processing was given to sixth form students at **Saffron Walden County High** and in November 2013 a talk was given at the **University of the Third Age** on manufacturing at the speed of light, which also included a discussion on the future of manufacturing.



Educational Demonstrator Programme

After brainstorming sessions and interaction with local school children the theme and focus of this educational outreach programme was decided. The theme is entitled **'Watch it Made'**.

Watch it Made has a high level objective which is to enable all 12 and 13 year olds in the UK, some 650,000 children each year, to produce a quality self-designed and self-manufactured watch. A watch is a product that can be used every day and is an item which demands the application of precision engineering. The Watch it Made concept will draw on learning aspects of design, manufacture and assembly. It is envisaged the programme will include processes such as CAD, CAM, additive manufacture, micromachining and microscope-based assembly. Other higher level learning aspects could be added such as dimensional and geometric tolerances, precision mechatronics and adhesive technologies.

The broad thinking behind this idea is that all school children in UK will gain appreciation of making an engineering product, one they can be proud of producing and regularly use. Importantly, they will gain this experience prior to their GCSE subject selections.

While the scope of this programme is ambitious, it has been considered in depth. A full roll-out across the UK will ultimately need the Watch it Made programme to become part of the school STEM curriculum. In recognition of this the engagement of leading STEM programme advisors is secured via the established networks of the Royal Academy of Engineering.

The Watch it Made programme will be first tested in one or more selected regions during 2015. To achieve this goal a number of industrial partners will be secured during to 2014 providing much needed resources and facilities.

A local SME, Fusing Creativity, has been engaged to develop the branding and promotional material needed for the Watch it Made programme. A website domain **www.watchitmade.org** has been secured and the related trade name is being registered. A detailed 'Watch it Made' project plan and costing for national roll-out will be developed during 2014. An MRes group project from the Centre for Doctoral Training in Ultra Precision will facilitate this project advancement. Four Cambridge students from the second cohort have opted to engage into this programme.

Future Outreach Events

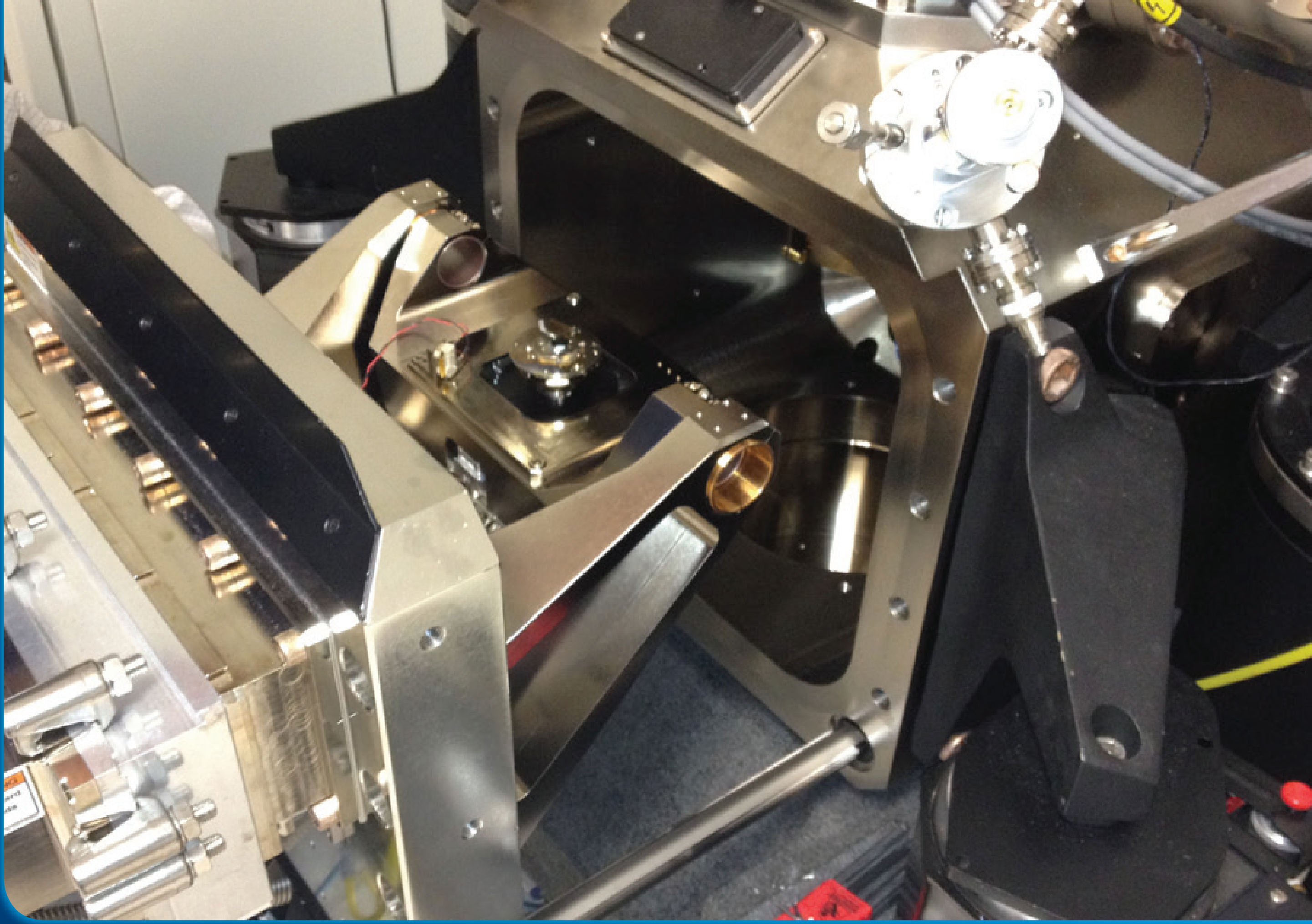
Planning is in progress to deliver an industrial short course and themed one-day meeting before the end of 2013.

The Precision Engineering Industrial Short Course will be held at Cranfield University in November 2013. The Centre has organised an industrial precision engineering short course based on the highly successful series developed by Professors Pat McKeown, John Corbett and Paul Shore at Cranfield. International lecturers, Prof Martin Culpepper of the Massachusetts Institute of Technology and Prof Robert Munnig-Schimdt of the Technical University of Delft are supporting this course proving world leading kinematics and mechatronic expertise.

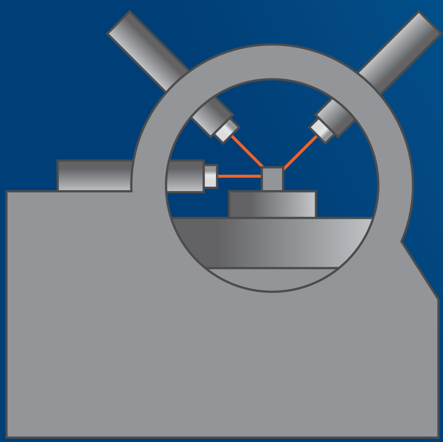
A one day themed meeting, *'Metrology Technologies to Enable Reel-to-Reel Processing of Emerging Products'*, will take place at the National Physical Laboratory, Teddington, in November 2013 with speakers from industry, academia and other EPSRC Centres for Innovative Manufacturing.

Research focused meetings will be organised to take place in 2014, with the aim of delivering a topical networking meeting every quarter. These themed meetings will be held at places of industrial and academic relevance bringing together key people from across the ultra precision community. The first themed meeting *'Plastic Electronics Fabrication Technologies'* will take place in February 2014 at the Centre for Process Innovation Limited in Sedgefield and the second *'Future Display Technologies and Production Demand'* is planned for April 2014 at the Institute for Manufacturing, University of Cambridge. Subsequent meetings on Reel to Reel Production Technology and Micro Surface Structuring are planned for mid to late 2014.

The Centre also plans to exhibit at Photonics West 2014, to be held in the US in February, in conjunction with other EPSRC Centres. An exhibition stand will also be considered for eu**spen**'s 14th International Conference in Croatia, June 2014.



Nano-FIB



Original schematic of Nano-FIB concept

The Nano-Focused Ion Beam (Nano-FIB) research platform is intended to offer a rapid production capability for devices that require sub-10nm precision on a range of materials of interest to the precision engineering community. A design study for an ultra precision machining platform has been established with all major sub-systems considered, including the sample positioning and automation mechanisms, ultra-fast laser tool, atmospheric plasma tool and the metrology suite. In addition to the major sub-systems, additional machine interfaces were addressed, including the He/Ne/Ga FIB, the environmental effects and structural considerations.

A brief description of the major sub-systems follows:

Sample Positioning

An interferometer-controlled stage will be employed, to ensure the highest possible positioning accuracy. In addition, an interferometer configuration is suggested in order to monitor both rotational and translational error motions in all axes, allowing for optimal stage control during FIB, ultra-fast laser machining and associated metrology. With regards to an alignment system, a pre-alignment process was selected to define the orientation of the sample automatically relative to a global coordinate system. An enhanced global alignment algorithm is under development to link the sample coordinate system to the coordinate system of the high precision laser machining and metrology subsystem.

Atmospheric Plasma

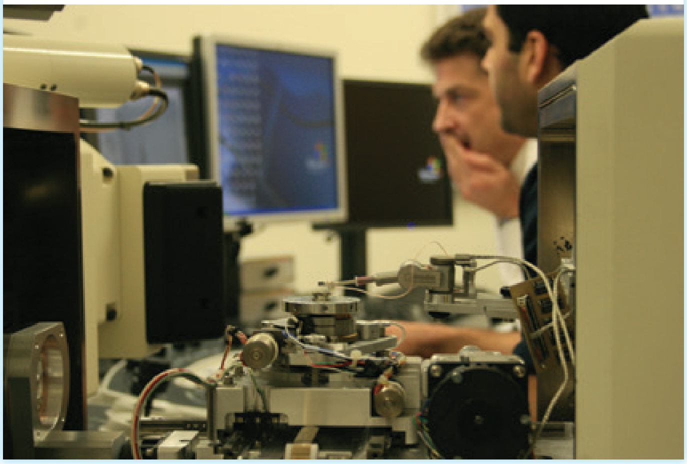
A micro torch design being developed at Cranfield University will be integrated into the system with the ability to etch silicon-based or silicate materials. This type of tool can also perform plasma cleaning to remove organic residues and dust from laser-based processes. Material deposition capabilities are being proposed for oxide layers, polymers and carbon nanotubes (to which additional attention will be given because of the growing interest in this research area for functional devices).

Work on the Nano-FIB sub-systems continues and will remain a significant activity within the Cambridge arm of the EPSRC Centre in Ultra Precision in the coming months. The installation of the He+ FIB system is planned for January 2014, which is a nine-month delay on the original target of April 2013. This is due in part to the higher specification and costing of the FIB column and the associated lead-time of this component.

It does however significantly advance resolution limits of the Nano-FIB platform from a planned 40nm to around 3nm, placing it in the category of one of the highest resolution machining systems in the world, which will significantly extend the range of device fabrication within the Centre. Our ultra precision machining solution will be complete by April 2014.

Laser Tool

A fibre laser source was selected having a repetition rate of 2MHz and pulse length below 400fs. This will be driven by a high resolution Acousto Optic Deflector (AOD), capable of altering beam position in 10.3μs. The combined AOD and laser will be able to produce structures on the sub-micron scale with the use of bespoke correction optics.

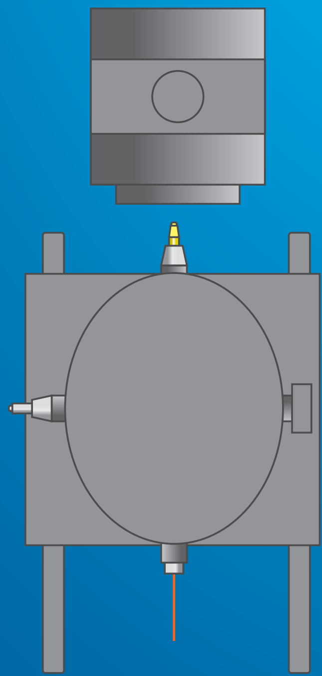


Metrology Sub-System

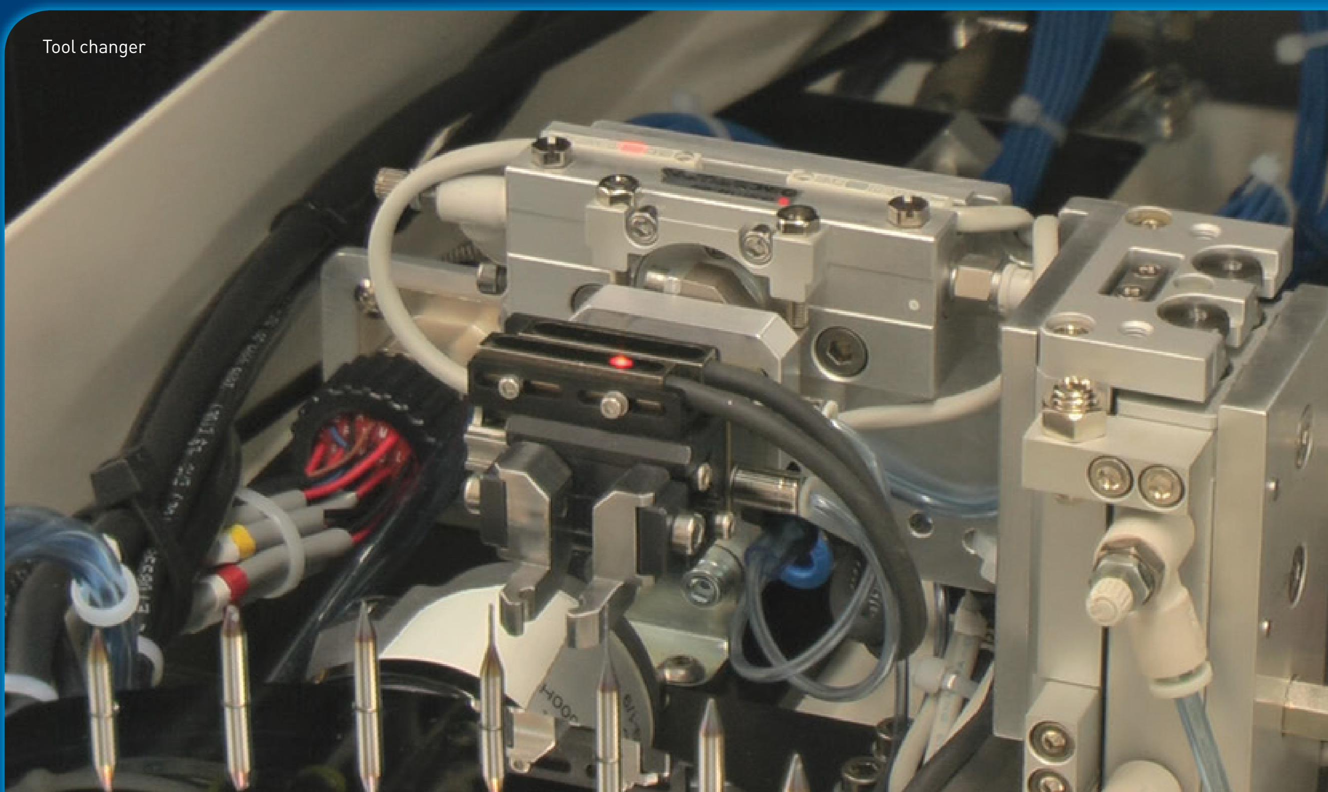
Measurement techniques such as scanning electron microscopy, ion beam microscopy, scanning probe microscopy, interferometry, holographic microscopy, and X-ray computed tomography were reviewed. In particular, the promising prospect of using the helium ion microscope for 3D topography measurement and digital holographic microscopy could offer the most versatile optical profiling technique for high resolution imaging. The combination of helium ion microscopy and digital optical and ion holographic microscopy offers a very wide spectrum of measurement capabilities.

Meso

The meso-scale research platform is intended to provide an effective production capability for devices that require sub-100nm features and accuracy levels on substrate parts of up to 100mm.

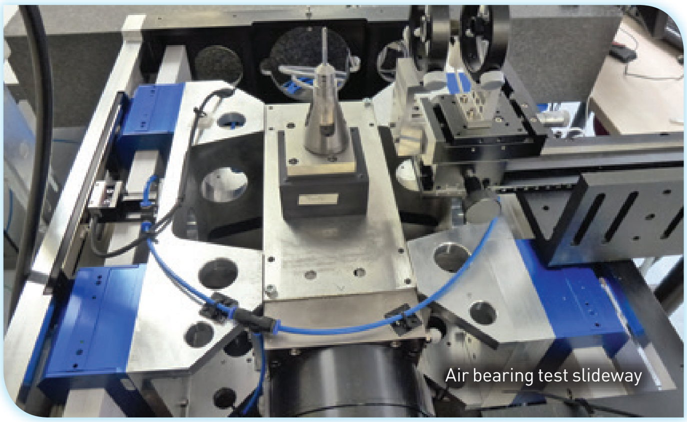


Original schematic of Meso platform concept



Tool changer

After internal and external international reviews of project plan, it was decided that this research platform would be developed based around a highly novel ultra-compact machine concept entitled µ4. The µ4 concept enables multi-axis precision CNC machines to be realised at the scale of a domestic 'white goods' appliance. The design development of this machine concept has significantly progressed in terms of its bearing technologies, design for effective manufacture and application of selected process technologies. Advancement of an automatic tool changer system has also taken place. Key process investigations have included the miniaturisation of reactive atom plasma torch systems and energy supply options.



Air bearing test slideway

In-Situ Metrology

Metrology of small-scale components, especially those having sub-micron scale features, is made more complex if the component part is moved or re-clamped during processing. Developing metrology technologies that can be applied directly on to machine tools have key benefits. For the meso-scale research platform a specific metrology development is being carried out that will enable an automated method to machine small parts with fine features. The objective of the applied methods is to develop in-situ part measurements that prove an automatic error correction to be applied in an automatic mode. A PhD student project funded by Hexagon Metrology based at Cranfield University is creating this automated measuring capability.

Work on the meso-scale platform continues and will remain a significant activity at Cranfield with expected laser beam technology contributions from Cambridge appearing in late 2014. A detailed specification for the platform will be finalised in early 2014. From this specification significant research activity and industrial resources will be applied in building the complete system. Key research findings from the linear test system, fluid film spindle technologies and metrology investigations will be incorporated into the overall system specification.

The following are the key sub-system developments:

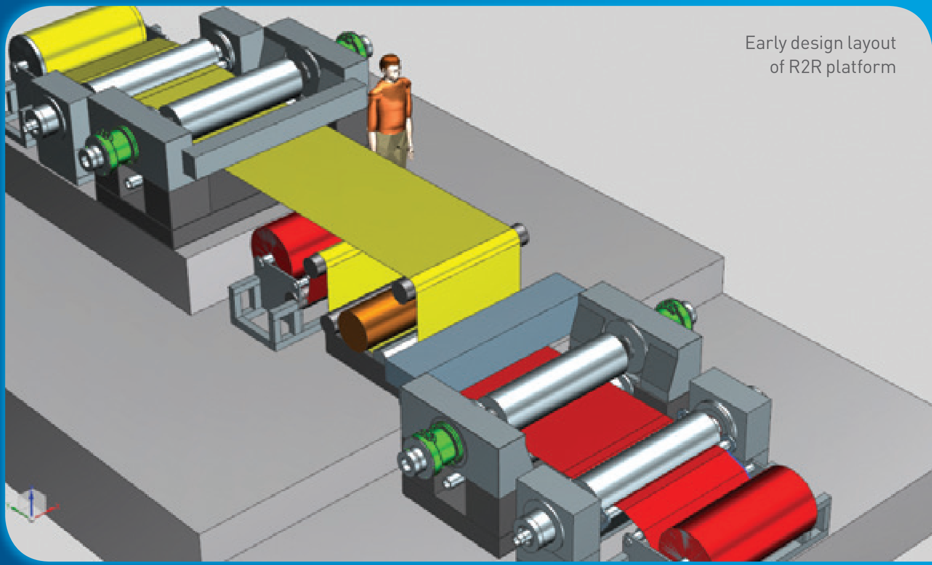
Air Bearing Linear Motion Technology

In order to study the dynamic positioning performance of highly compact linear motion systems it was necessary to build an independent linear sub-system demonstrator. This sub-system has been assembled and commissioned. This air bearing-based linear unit employs porous graphite air bearings which can be directly evaluated against other bearing systems. It will also allow research investigations surrounding the selection of differing encoders. Advanced linear encoders have been provided by leading suppliers. Commercially provided servo motion control optimisation features are being tested, including where additional inertia influence takes place through movements of attached motions.

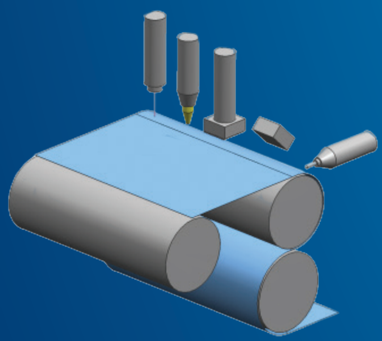
Microwave Based Reactive Atom Plasma

Preliminary tests have been performed to assess the material removal of optical glass using a microwave plasma torch provided by Adtec. The results have led to further investigations in the fundamental understanding of SF_6 gas in argon-based microwave plasmas. Susanne Cumberland, a UK PhD student, is undertaking research into this novel microwave reactive atom plasma (RAP) technology with the aim of creating a highly deterministic and efficient plasma beam. She is sponsored by Gooch & Housego with the specific task of developing energy beams for the processing of advanced optical components used in precision optical and AOM systems.

In parallel, a self-funded international PhD student, Nan Yu from the Harbin Institute, has been tasked with researching small scale radio frequency (RF) torch designs. This work will provide the foundation for some novel energy beam hardware. The proposed new RF plasma torch designs will enable the surface correction at a wider range of spatial frequencies. This spatial demand is critical for high end optics fabrication. In the meantime, Dr Renaud Jourdain has been working with the US companies JJP Consulting and Comdel Generators to establish higher reliability and stability of existing RF plasma systems. Coaxial Power Systems, a UK SME, has also been approached and has expressed interest in plasma generator design development.



Early design layout of R2R platform



Original schematic of R2R platform concept

Reel to Reel

The reel to reel (R2R) research platform is intended to provide an effective production capability for film-based products and devices. Significant background research into R2R processes has been done, including detailed studies of published material, international road mapping outputs and through road mapping performed by the EPSRC Centre in Ultra Precision itself. The Centre commissioned a specific study investigation by iXscient Limited. Through this activity in September 2013 the Centre took part in an industrial outreach tour of Korean companies that make active film-based products. This industry awareness tour was funded by the Department for Business, Innovation and Skills.

Progress on realising the R2R platform has been made in four key areas:

- Defining the functional requirements
- Creating a web/film steering test rig
- Establishing effective rotary systems solutions
- Building a demonstration roller for passive film fabrication

Functional Requirements

Key functional demands for the R2R platform have been set as follows:

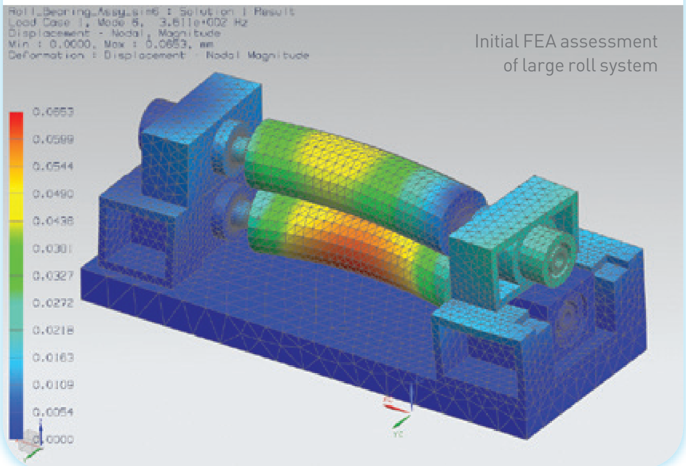
Function	Specification target
Longitudinal and lateral film positioning capability	Film of up to 1.4m wide at 0.001mm accuracy levels
Precision lamination of 2 (or 3) films	At speeds of >3m/min with alignment accuracy of 0.005mm
Passive film fabrication using gravure technologies	1.4m scale film width
Precision motion controlled ink jet printing	0.005mm accuracy
Precision motion controlled laser processing	0.005mm accuracy

Film Handling Test Rig

To advance understanding of film handling and to enable a means to verify analytical models, a film handling test rig has been produced. The project was sponsored by M-Solv, Fanuc and Heidenhain UK. An overview of the group project from start to end can be seen in the video on the Centre's YouTube Channel: **www.youtube.com/watch?v=KzguWVLyTtQ**

Large Scale Film Roll Technology

After some preliminary design and finite element analysis an initial 1.4m wide 400mm diameter roll has been detail designed and is under manufacture. It is being manufactured by the Cranfield team operating the EPSRC established UPS² IKC Structured Surfaces Laboratory based at Optic Glyndŵr in North Wales. This initial drum will be employed in research trials with the aim to imprint fine grating features using a gravure method. These instrumented films will subsequently be employed as the test parts which will prove the capability of the R2R systems functional requirement for precise and rapid film positioning.



Initial FEA assessment of large roll system

Rotary Motion Technology

A critical machine technology for any reel to reel film processing system is associated with the primary rotary motion systems. Industry standard systems having capacity to move 1.4m-length rollers weighing over 200kg will have an accuracy of axis of rotation in the range 0.002 – 0.004mm (2 – 4 micrometres) as this is the limited accuracy level offered by rolling element bearings. Clearly, this level of motion accuracy would not enable achievement of the functional demands specified for the R2R system.

High precision spindles as used in ultra precision machines were reviewed for applicability to the R2R platform. The key findings were that dynamic positioning bandwidths were not clarified, speed ranges were wider than that needed for film processing, cost was extremely high, and availability was restricted to supply of special units.

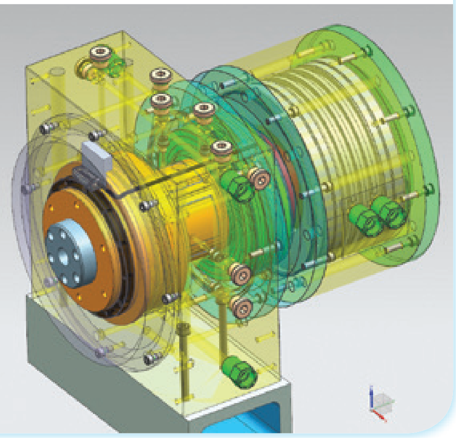
It was therefore decided to develop a fluid film spindle technology that was defined specifically to meet the R2R film processing parameters. UK companies were engaged to support the fabrication of component parts and the necessary coatings for specific items. UK metrology systems were also specified along with some European sourced motor units. Hydraulic services and cooling units will be sourced through UK companies active in this area.

The R2R platform spindles under manufacture have been optimised in the following aspects of design: bearing design; fluid film parameters; materials selection and preparations; encoder and motor selection and positioning.

Gang Zhao, an international self-funded MSc by Research student, is performing aspects of fluid film bearing design and will perform validation testing of the R2R spindle system development. A UK PhD student, Peter Xia, is undertaking research into the materials selection and surface treatments needed to achieve high performance of critical bearing components.

Two spindle units of an initial design are under fabrication and will be performance tested in early 2014.

Diamond turned bearing part



CAD image of initial hydrostatic roll spindle

The R&D Portfolio

In-Process and Post-Process Metrology for an Ultra Precision Machine

Jake Larsson

This project involves the research of micro-part measurement technologies with the aim of developing a metrology technology for implementation on to a meso scale research platform located in the EPSRC Centre in Ultra Precision. Activities will include mechanical, optical electromechanical, and software developments that should realise a leading and traceable metrology capability functional in an automatic mode.

Meso scale platform

Sponsor: **Hexagon Metrology**

Optical Quality Wear Resistant and Diamond Turnable Coatings for Aluminium Hydrostatic Bearings and Rollers

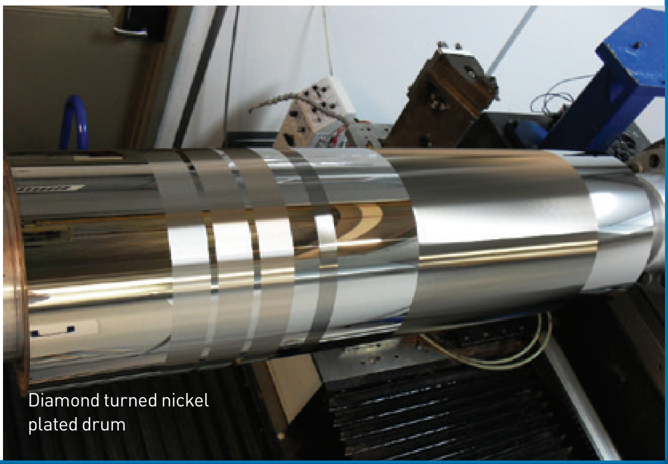
Peter Xia

Aluminium and steel rollers are used in a number of applications but of particular interest is their use in reel to reel production such as with plastics and electronics production. The rollers should be hard, defect free and diamond turnable to an optical quality surface to support micro features.

The rollers are typically coated with copper or nickel deposit. The electroless nickel is limited to 200μm thickness (porosity issues occur with thicker deposit). This is not always thick enough to accommodate the required features to subsequently diamond machine into the deposit. Another challenge is that the plating processes replicate the surface structures underneath them with great fidelity so a good starting base is essential.

In a commercial plating house, stray particulate matter adhering to the surface will be replicated during plating and may appear as voids or defect during subsequent diamond turning of the coated roller. Despite the large size of the rollers, small defects will cause the roller to be scrapped.

The purpose of this project is to recommend modifications, improvements to the current processing of optical quality wear resistant diamond turned coatings to enhance the quality and reduce the defect rate of rollers and hydrostatic bearings.



Diamond turned nickel plated drum

Development of an Ultra Precision Film Steering Test Facility

Betty Cabon / Sahil Chouhan / Amira T. El Araki / Miguel Camilleri / Maud Pfleger / Praveen Rao / Martyn Webber

Currently flexible displays are manufactured using a step-to-step stacking process, which is a time consuming and expensive process. The production of displays is set to be revolutionised and soon, displays will be made from very thin flexible glass substrates. Within five years, displays are expected to shift to being produced on plastic films. The age of thin glass and plastic based displays will transform how we think of them. A massive growth in use of low-cost displays demands production is made much more rapid using reel to reel (R2R) techniques. These techniques will, to the untrained eye, look like paper production, yet in reality they will be operating at the precision of the microelectronics sector.

As part of Cranfield University's Manufacturing and Materials MSc Programme, the Centre supported a 12-week group project to research the development of an ultra precision film steering test facility. The aim was to understand, specify, develop and build an ultra precision four-axis computer numerical control (CNC) thin film positioning facility, in an almost impossible timescale. The CNC controlled motion system had to be capable of positioning thin films of glass and/or plastics at high speed.

The group project team consisted of seven students, each working in different areas of the project and by the end of the project period, a system was designed and an ultra precision film steering test facility was built, including the control system design and the majority of the hardware and software integration.

An overview of the group project from start to end can be seen in the video on the Centre's YouTube Channel: **www.youtube.com/watch?v=KzguWVLyTtQ**

Sponsor: **M-Solv, Fanuc, Heidenhain UK**

Ultra Precision Film Steering Test Facility

Femto-Second and Nano-Second Pulsed Laser Machining of Carbon Nanotubes for Field Emission Applications

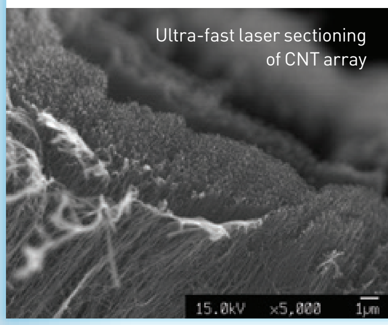
Francisco Orozco

This work focuses on the production of field emission devices with applications from space thrusters to LCD backlights. The material used was carbon nanotubes arranged as fibres and films. Carbon nanotubes have been proven to have good electrical conductivity as well as good mechanical strength. These films and fibres were machined with two different laser sources to identify potential enhancement in emission properties of the material after being processed.

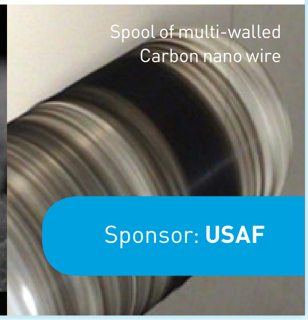
Lasers were used with varying pulse durations; one had nano-second pulse duration (10 ns) while the other had femto-second pulse duration (130 fs). The interaction of a nano-second pulsed laser causes the material to suffer from thermal ablation resulting in melting and ultimately vaporisation of material, leaving heat affected zones through the bulk material.

Ultra-fast laser interaction with matter will reduce these heat affected zones and it is believed that this low modification of the bulk material will produce an emitter with better field emission.

The outputs of this work will provide new production capabilities for future devices with enhanced emitter capabilities enabling industrial scale application of this technology.



Ultra-fast laser sectioning of CNT array



Spool of multi-walled Carbon nano wire

Sponsor: **USAF**

Microwave Plasma Technologies for Optical Processing

Nan Yu

The research aim of this project is to increase the quality of plasma processing at atmospheric pressure and to provide faster processing rates compared to that of ion beam figuring. The process is a key element in providing an optical fabrication capability for high precision optics.

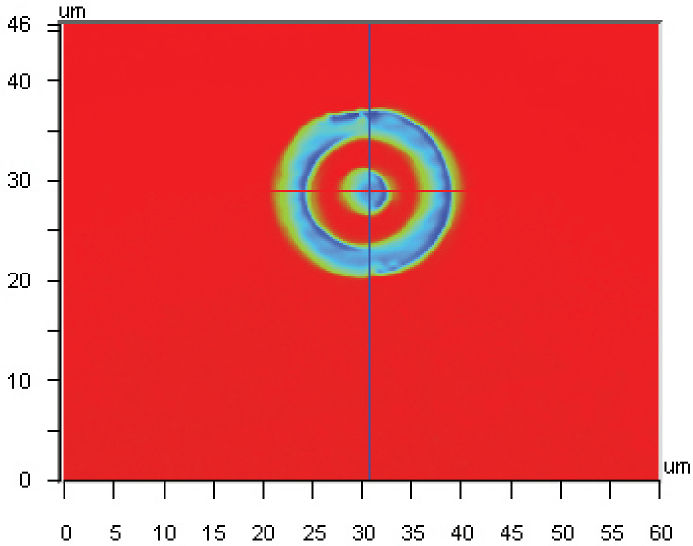
Holographic Optical Fibre

Jiho Han

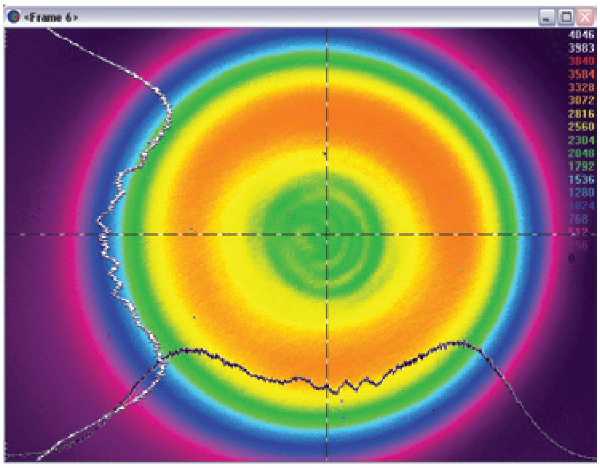
This research project has investigated the feasibility of a holographic optical fibre that could project an arbitrary image directly from it. The most promising and immediate potential application is beam shaping, though it may also be useful for beam splitting, or low information content display, such as indicators.

A Matlab program was developed that takes a desired image and calculates the 'best' phase hologram. It uses the Gerchberg-Saxton algorithm to find the phase hologram, and Rayleigh-Sommerfield's diffraction formula with Fresnel and Fraunhofer approximations for calculating the wave propagation.

In order to experimentally demonstrate the holographic optical fibre, a FIB system is selected as the machining platform, and a fibre mount is designed to ensure geometric compatibility. A hologram for a ring shaped beam is calculated, and the features simplified to aid ease of manufacturing. On coupling a laser into the fibre, the ring beam profile results as predicted. The figure shows the surface profile measurement of the holographic optical fibre tip, and beam measurement for the output beam. The step height in the hologram is approximately 700nm, and radius/distance from fibre tip for the output beam measured 0.083 as compared to the predicted 0.1. Potential further work includes machining holograms for more complicated shapes, study on suitable integration into laser systems, and investigation for suitability for high power lasers.



Surface topography of FIB processed fibre end-face


Transmitted beam profile

Sponsor: **IPG Photonics**

Microwave Plasma Technologies for Advanced Surface Fabrication

Susanne Cumberland

The aim of this novel energy beam research project is to investigate new microwave plasma technologies for the surface figure correction of optical components. The research objective is based around creating a lower temperature plasma processing technology applicable for advanced optics and potentially thin glass films. Initial test work will be based on a pilot 300mm size capable RAP research tool. The research ambition will include improvement of tool (plasma torch) stability enabling reduction of surface features such as mid-spatial frequencies (MSF). Other surface features caused by plasma processing such as those associated with heat will also be advanced.

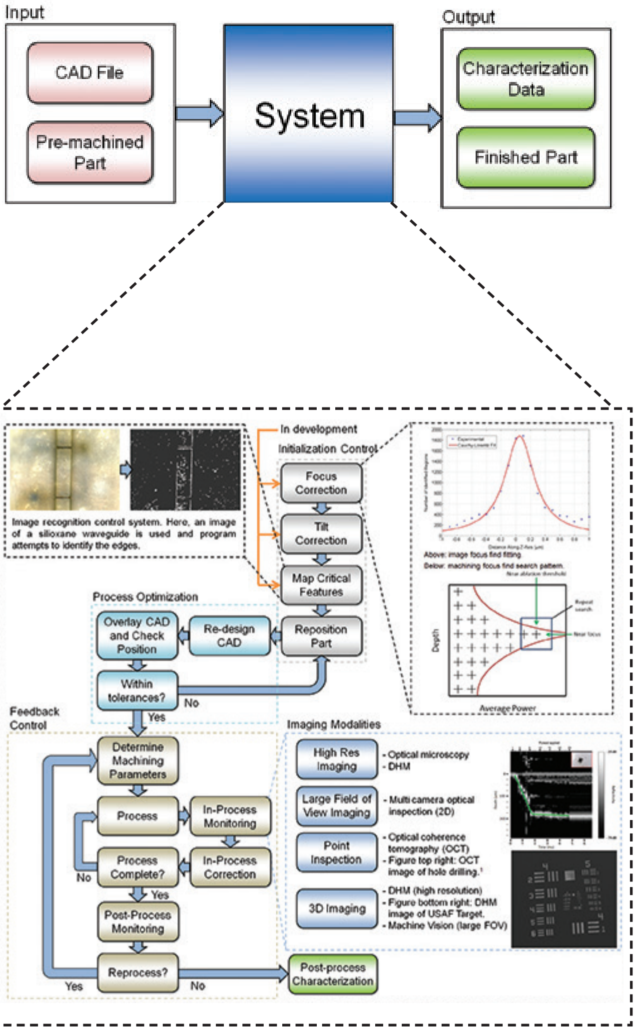
Sponsor: **Gooch & Housego**

Control System for Ultra Precision Processing

Karen Yu

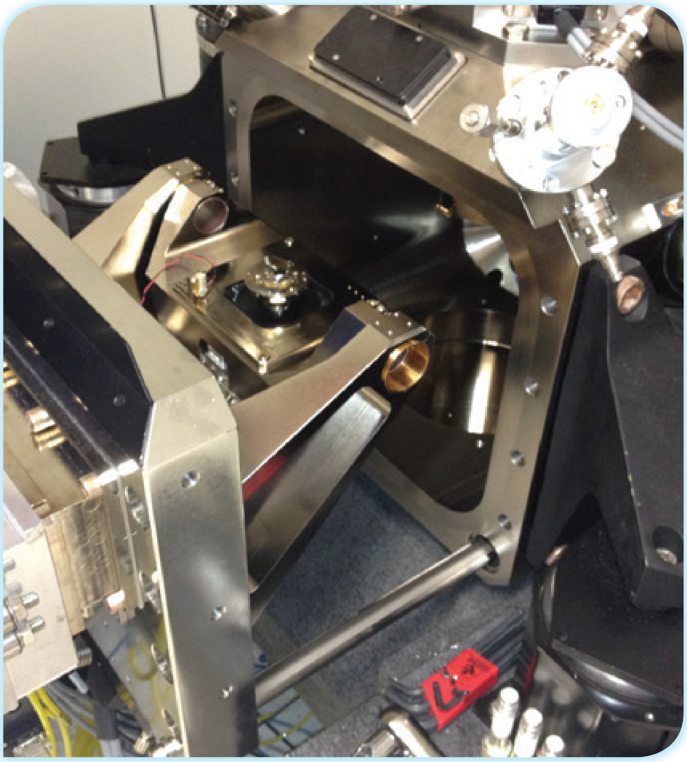
This project proposes to advance the state of prototyping and production of precision laser machining processes. Current production methods suffer from the inability to apply feedback and/or monitor processing in situ, leading to increased costs in production.

This project will combine an imaging and processing platform to create a control system that will automate production, quality control and identification of optimal machining parameters for known and unknown materials. When complete, the system will be able to provide 3D data on hole evolution during laser ablation as well as monitor and improve on carbon nanowire machining, TEM lamella preparation, and rapid prototyping of carbon nanowire FET arrays.



Architecture of the proposed in-process metrology system

Sponsor: IPG Photonics

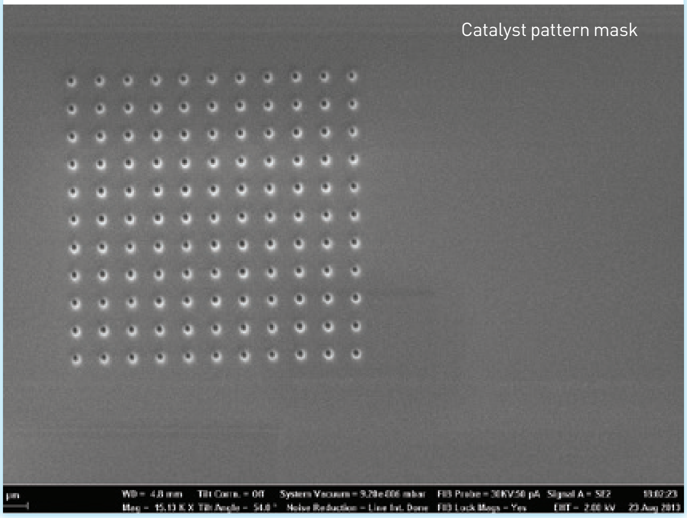


Ultra Precision Light Sensor

Chris Williamson

The device currently being developed is based on field-emitting carbon nanotubes (CNTs). Initially a dense forest of nanotubes was grown on a silicon wafer, but field emission was minimal owing to the lack of any protruding peaks. These high aspect-ratio peaks are critical for field emission, and so research was carried out into methods for high-speed patterning of individual CNTs.

A patterned catalyst is deposited and chemical vapour deposition is subsequently used to grow individual nanotubes from the catalyst. For an individual nanotube to be grown, a catalyst of ~100-200nm diameter is required. The figure shows the mask used to generate the patterned catalyst.



Catalyst pattern mask

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

Wenhe Feng

An experimental technique has been developed that can give micro-tunnels and channels on a fused silica substrate *(Spectrosil 2000)* using 800nm and 1030nm ultra-fast lasers and subsequent etching. The minimum tunnel size is 10*25μm^2, with a maximum measured length of 1.4 mm. Channels have been generated with widths down to 65μm up to 114μm deep.

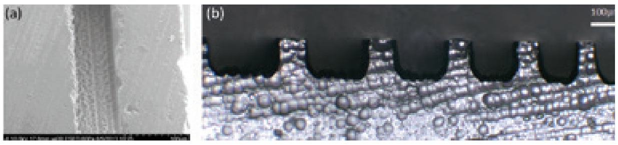
Etching was done with 35.9% (w/w) KOH at 80°C in an ultrasonic bath for tunnels, and 120°C without the bath for channels.

Preliminary results have shown:

- Multiple laser-written lines can be stacked up to the desired dimension of the feature
- Repeated laser exposure prevents etching
- KOH was found to have less self-termination in long tunnels than the more conventionally applied HF
- The surface finish of the component is different on the side and base of the channels

The basic parameters are:

Laser	Hurricane *i*	Satsuma
Pulse duration (fs)	130	280
Wavelength h (nm)	800	1030
Focal spot size (μm)	5.4	7.2
Repetition rate (kHz)	5	125
Polarisation	Circular	Circular
Pulse energy (μJ)	1.85	1.0-3.4
Writing speed (mm)	0.5-2.0	0.05-10
Writing depth (μm)	100-200	0-150



(A) SEM image of a tunnel side wall (sample was cleaved)
(B) Side-view of the channels with varying overlap distance of the laser-written lines from 30 to 5μm

Further study is being done on the process mechanism and its outputs. Quantitative evaluation of the feature quality, improvement of consistency of the FLICE process and the application of FLICE technique for MEMS fabrication is also on-going.

Sponsor: **Amplitude Systèmes**

Assessment of the μFour Machine Based on the Processing of Complex Features

Oliviero Corinaldi

The μFour is a compact R&D machine capable of both micro-milling and diamond turning. The aim of this research is to assess its capabilities with emphasis on repeatability. To achieve this, several features were selected from a component of the Swatch Group. The project focused on both programming the CNC codes and machining the parts.

Based on inspection of test parts, further analyses were set to assess the machine. These helped identify machine flaws and suggested the presence of geometric errors such as lack of parallelism of X/Y axes and alignment errors between tool and workpiece.

The components were completed and the assessment of the machine repeatability was tested with a Tesa Visio 300 dcc. Initial results indicate good repeatability (<15 μm) although motional settings need attention. Once the alignment defects are rectified, the μFour should have great potential.

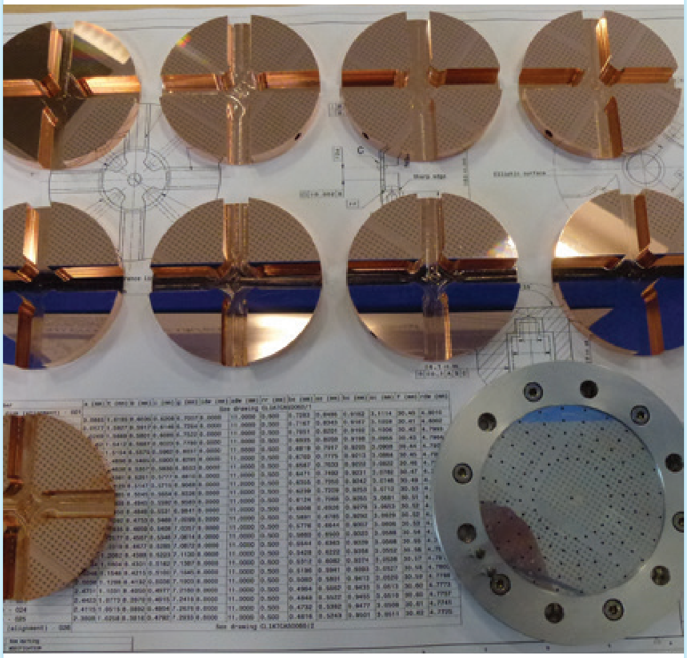
Sponsor: **Swatch Group and Loxham Precision**

Dimensional Deviations of CLIC Standard Discs During Machining Operations

Bastien Moreau

The European Council for Nuclear Research, better known as CERN, develops novel accelerators with brand new technologies, like the Compact Linear Collider (CLIC). With an expected length of 48 km, this accelerator is intended to reach energy of 3TeV for colliding electrons and positrons.

To produce this accelerator, more than seven million standard copper discs are required. To guarantee a perfect bonding, CLIC engineers have imposed a set of sub-micron tolerances (flatness, shape accuracy), combined with a severe roughness tolerance (Rt <25nm). To fulfil these requirements, high precision engineering is needed to develop an accurate and cost effective manufacturing process. Diamond machining is a key technology for this.



The project provided a complete study on dimensional deviations in milling the wave guide. A literature review combined with experimental work using a Kern micro milling machine was undertaken. Computer Assisted Machining (CAM) simulations were carried out using Feature CAM 2013 software to generate the complex tool path for cross milling operations. Distortion on the back surface of the disc was measured using phase shift interferometers at different depths of cut and feed rates during the rough milling process using carbide tools.

Sponsor: **CERN**

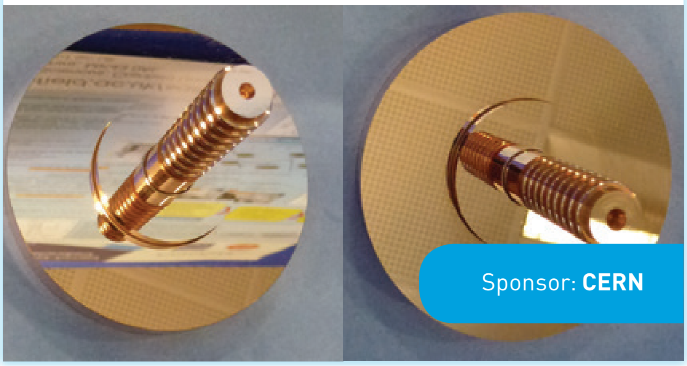
Analysis of Diamond Turned Surfaces of CLIC Standard Discs

Cindy Potyrala

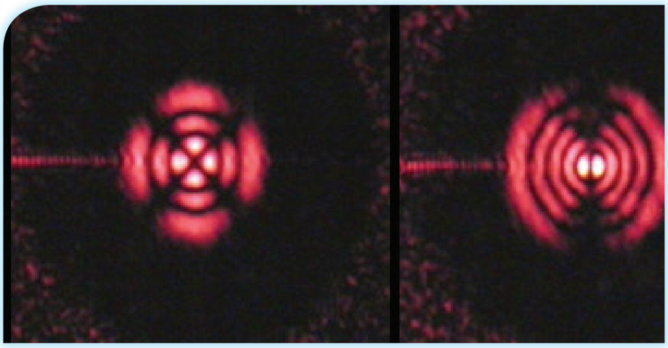
The surface finish of Compact Linear Collider (CLIC) copper discs and radio frequency (RF) are essential as they undergo a diffusion bonding process. The discs can become marked and they damage easily. The surface texture achieved is highly affected by the diamond turning operation. The copper discs have sub-micron tolerances and nanometric surface roughness requirements.

A scratch study was carried out to define a maximum size of scratch that can be tolerated as the discs are subjected to an etching process. Measurements before and after etching of maximum height peak to valley (Pt), depth and width of the scratch were performed. All parameters show a tendency to decrease after etching. The scratches with a Pt below of 1.5 μm before etching decrease up to 1 μm after the etching process.

Disc surfaces and the critical iris features were also diamond turned at different feed rates to analyse the influence on the surface finish and form accuracy. When the feed rate increases, the surface roughness average (Ra) increases. An optimum feed rate exists and test results will indicate this.



Sponsor: **CERN**

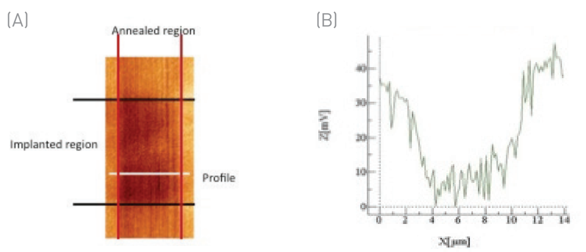


The Use of Ultra-Fast Laser Annealing to Remove Ion Beam Implanted Gallium

Matt Bannister

This project aims to deliver an ultra-precise method of driving the removal of gallium ions implanted within substrates after focused ion beam micro-processing by using ultra-fast laser pulses below the optical damage threshold of the material. A mechanism of ultra-fast laser annealing has been identified from literature, whereby an ultra-fast melt-phase is induced within the focal volume of the laser. It is thought that gallium ions can then diffuse away from the region due to a concentration gradient, and the substrate structure re-solidifies after the laser beam has been removed.

Initial investigations carried out on glassy carbon and silicon have shown a decrease in gallium ion concentration, inferred from surface potential measurements by kelvin probe force microscopy, on the amorphous glassy carbon but not in the crystalline silicon. Work is on-going to find changes in gallium concentration through the depth of the material, and to investigate various laser-processing parameters on the changes in gallium concentration. Future investigations are to be carried out on glassy carbon, with the aim of using the technique to drive the removal of gallium from focus ion beam manufactured nano-embossing stamps.



(A) KPFM image of glassy carbon implanted with gallium ions at 30 keV and a dose of 1.87 x 1020 ions/cm^2 (B) Surface potential profile across annealed region showing a decrease in the region annealed with 800 nm, 130 fs Ti:Sapphire laser at a fluence of 5.4 J/cm^2.

Sponsor: **Carl Zeiss**

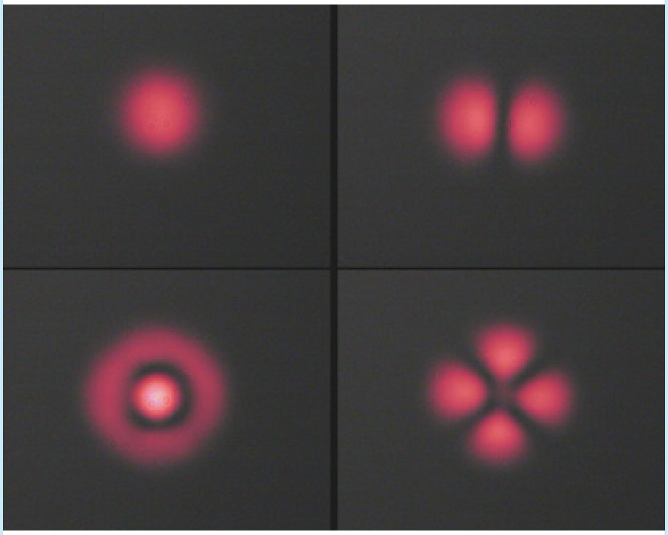
Holographic Enhancement of Fibre Optic Sensors

Jaliya Senanayake

This research investigates the effect that modal decomposition of a fibre has on fibre optic sensor devices, particularly focusing on enhancing their sensitivity. The aim is to develop a highly sensitive fibre optic dewpoint sensor.

The proposed sensor architecture is fibre, side polished at the sensing region and cooled using a peltier device. At dewpoint, condensate forms on the polished surface which interacts with the evanescent field exposed by the depressed cladding. This interaction results in an intensity modulation which is used for sensing. Being an evanescent sensor, the propagating fibre mode will yield varying penetration depths of the evanescent field, which affects the sensitivity.

Progress has centred on controlling the modal decomposition excited in the fibre using holographic launch techniques. The simulated annealing algorithm has been implemented, integrating super-resolution techniques to generate holograms that reconstruct accurate full phase LP mode profiles in the replay. Launching these fields into the fibre, selective mode launch is achieved. Sensing experiments without the mode launch have been done to determine the performance of the proposed sensor. Currently the mode launch is added to this system to investigate the performance of the device with a chosen mode propagating in the fibre.



Various laser launch modes

Sponsor: **Michell Instruments**

Residual Stress Measurement Using Focused Ion Beam

Raham Jahromi

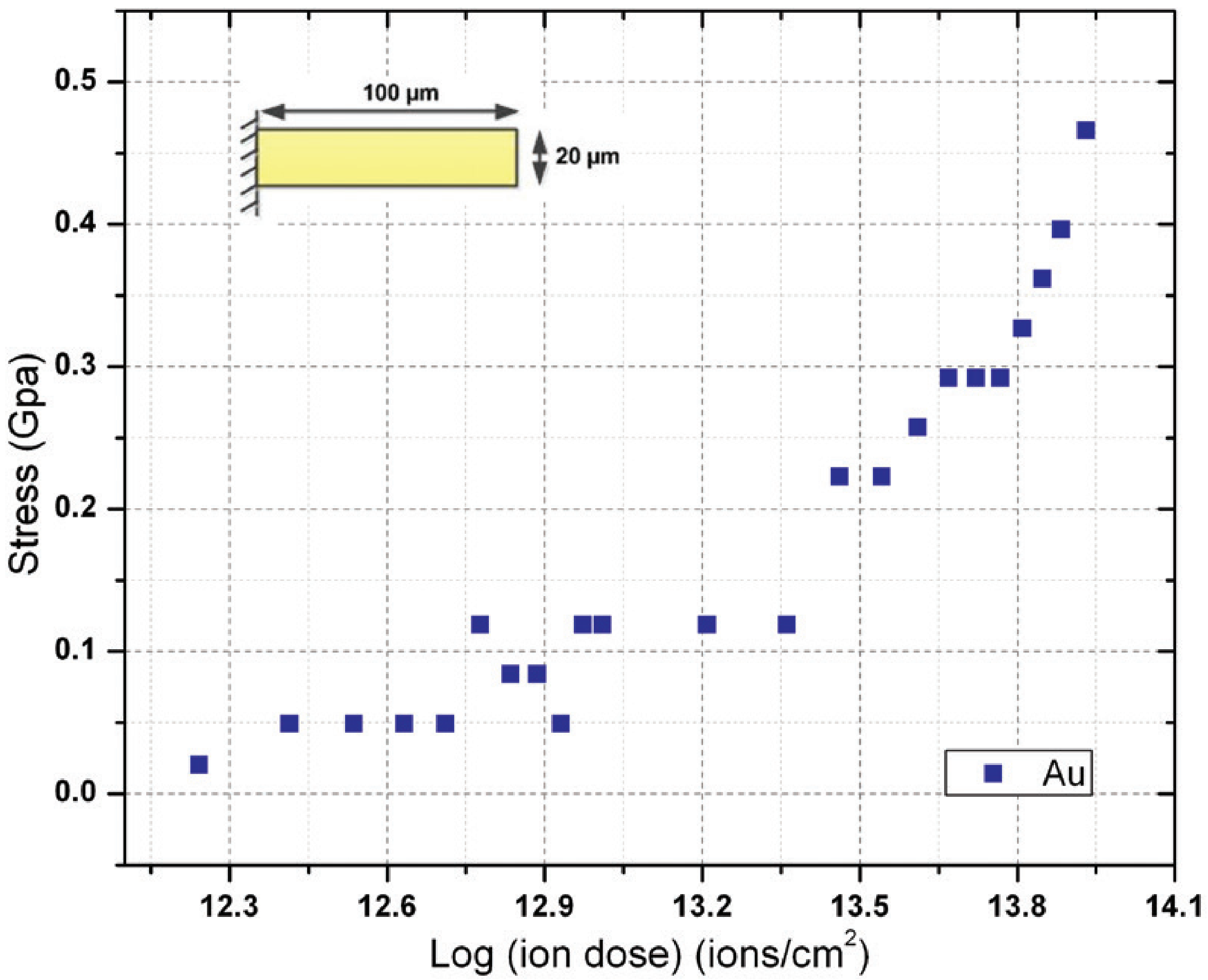
Depending on the growth conditions or preparation method used, thin films can be under tension or compression. If these values are too large they can affect both the lifetime of a device and its structure.

A technique based on focused-ion beam (FIB) system has been proposed. The advantage for such measurements is that it would be site specific and enable stress to be mapped on the sub-micron length scale. Unfortunately, as part of the FIB milling process Ga is implanted into the material being cut and damage can be created. A concern with this is that the implantation itself may affect the stress being measured and thus give erroneous values.

This project had two main aims: to investigate how much stress is induced into a range of materials by focused ion beam imaging and milling and to develop a method to measure the residual stress across a wafer.

To investigate the first aim prefabricated cantilevers coated in different metals were used. These were implanted with different Ga doses and the resultant deflections measured using secondary electron imaging. These experiments showed that for the films used, the stress induced during FIB imaging and milling exceeded the initial residual stress. This implies that FIB-based methods may have limited use. Also, the experimental results indicated that the stress induced may be dependent on the exposing and milling conditions themselves. If so it would be very difficult to differentiate between this stress and the original stress in the layers.

The second aim, to develop a technique that could map the stress across large areas such as wafers, could not be investigated fully since the membranes used kept breaking during FIB milling.



Graph of the change in stress (GPa) against ion dose (ions/cm^2) for Au cantilever sample. The sample had a dimension of 100 x 20 x 0.5 microns. Initially, the cantilever had a stress of 0.284 GPa.

Sponsor: **Carl Zeiss**

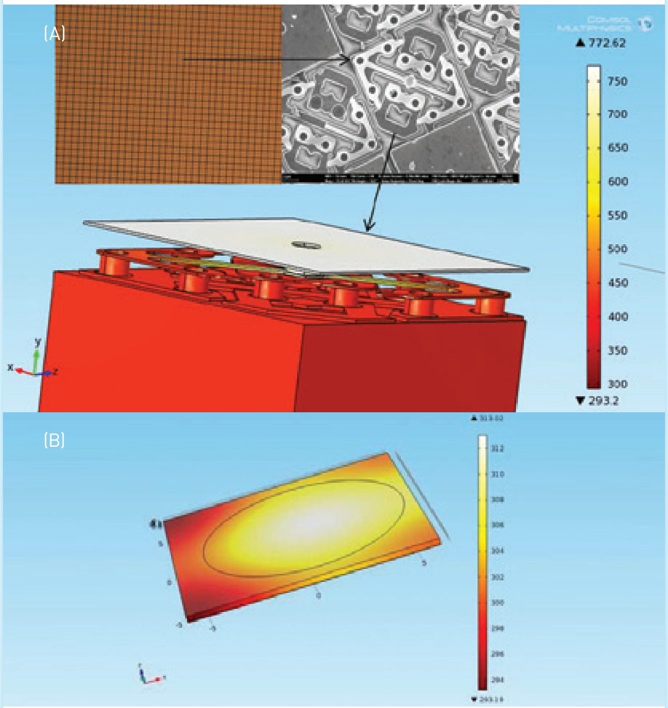
Spatial Light Modulators for High Laser Power Applications

Jon Parkins

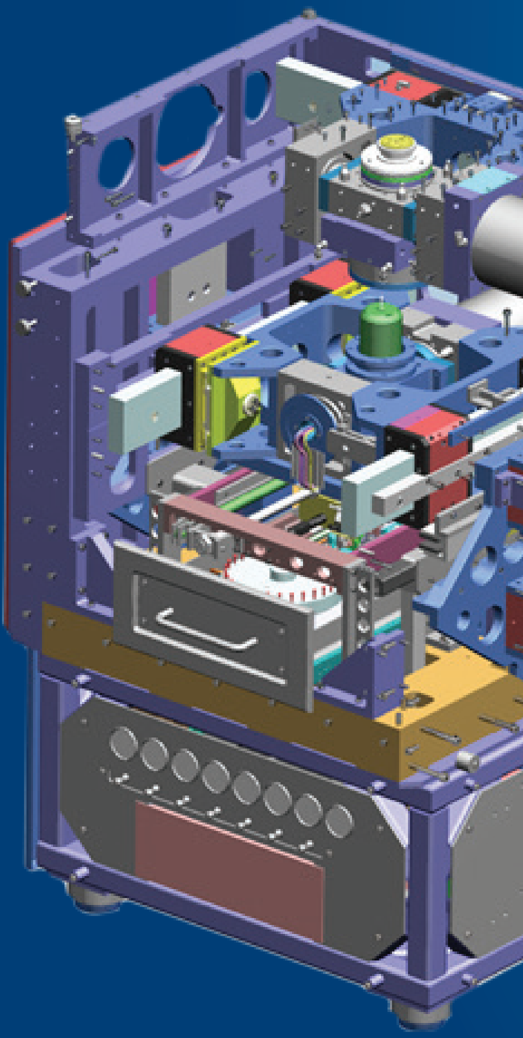
High powered lasers have significant applications in manufacturing and spatial light modulators can improve tunability. Current commercially available technology cannot handle the high powers required. This project investigated current devices, in particular liquid crystal (LC) and micromirror devices.

A finite-element model was built to simulate power handling capabilities of the devices. An LC device is predicted to handle a Gaussian beam of 8.33W with active cooling, clearly showing that LC devices are not a suitable technology for this application. Micromirror simulation predicted steering of a 550W Gaussian beam was possible with active cooling. Experimental testing featured a square top hat beam to illuminate the device and the temperature was measured using pyrometers. The non-cooled device showed significant visible melting damage after illumination with 150W of power from a fibre laser for 10s, with temperature measured approaching 480°C.

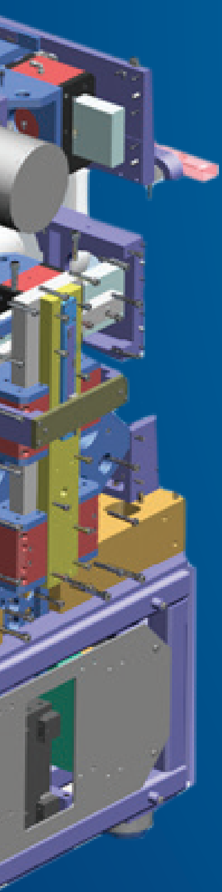
The model predicts 70W for this situation, with the discrepancy attributed to thermal diffusion into external device casing which was not considered in the model. Based on the findings, a new design and manufacturing route for an SLM were recommended to increase power handling performance.



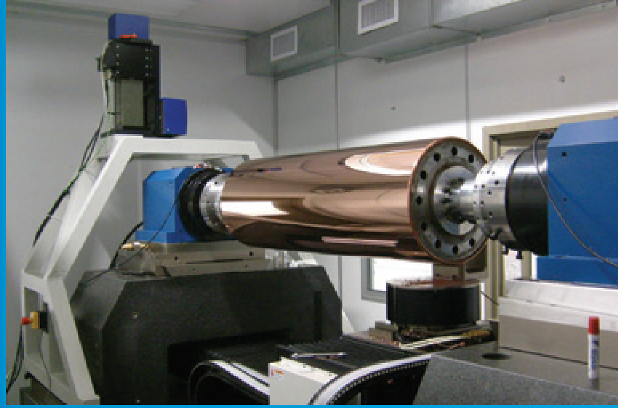
(A) Measurements made on commercial micromirror devices and the model based on them used to predict temperature profiles in a device pixel up until the material melting point. (B) Liquid crystal device simulation predicts failure at 8.33W even with cooling.

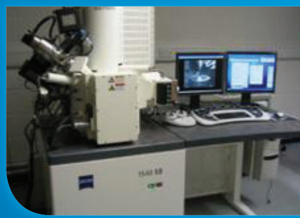


Centre for Doctoral Training



First MRes cohort 2012-2013





EPSRC Centre for Doctoral Training in Ultra Precision

Building on the creation of the EPSRC Centre for Innovative Manufacturing in Ultra Precision at Cambridge and Cranfield Universities in October 2011, the current phase of the EPSRC Centre for Doctoral Training is completing its first of three funded cohorts which will comprise 24 students in total.

The Department of Engineering at Cambridge and the Precision Engineering Institute at Cranfield have long been leading providers of engineering expertise across diverse fields. The new Centre for Doctoral Training in Ultra Precision brings together engineering, physics, chemical and materials expertise to provide leading-edge training and research in ultra precision.

The Centre is at the heart of one of the most innovative regions in the world, where research activities are focused on advanced materials, new production technologies and next generation products. By drawing on world-leading research competencies, a wealth of state-of-the-art ultra precision laboratories and the research platforms being developed in the EPSRC Centre for Ultra Precision, we aim to further develop our advanced training and research experience to equip the next generation of manufacturing leaders.

The existing Centre has received excellent external engagement through direct financial support of students and indirect support through industry-based research projects. Our current doctoral students receive wide-ranging technical expertise through a pioneering programme that delivers multidisciplinary research and training competencies from the two universities.

We propose to build on the success of the current Centre to address the manufacturing challenges identified in the new EPSRC Centres for Innovative Manufacturing in Ultra Precision, Large Area Electronics, Laser Based Production Systems and the Cambridge Graphene Engineering Centre.

Quality of the Team and Research Environment

The collaboration between Cambridge and Cranfield is a world-leading ultra precision partnership with laboratories and unique facilities at both sites better than at any 'blue chip' research and development facility in Europe. Developed as a result of significant investment from the Engineering and Physical Sciences Research Council (EPSRC) and the Higher Education Funding Council for England (HEFCE), these facilities give the Centre for Doctoral Training an unequalled practical foundation in the training of researchers and engineers with the capability for disruptive innovation.

The alliance reinforces relationships built in previous co-operations between investigators through the EPSRC-funded Grand Challenge, Innovative Manufacturing Research Centre (IMRC) and Integrated Knowledge Centre (IKC) programmes.

New partnering investigators bring expertise in emerging product developments. This aspect is 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.

The Training and Research Approach

The Centre for Doctoral Training in Ultra Precision offers a four-year programme, with a one- year taught Masters course followed – assuming a suitable level of attainment in the Masters – by a three-year PhD research programme.

The current MRes course builds upon the foundations created in the highly successful Ultra Precision and Structured Surfaces Integrated Knowledge Centre (UPS^2 IKC) EPSRC one-year MSc in Ultra Precision Technologies, delivered by Cranfield and Cambridge between 2008 and 2012. In that time the course produced 56 graduates, 64% of whom were from the UK, and 23% were female, a figure well above the UK average for postgraduate engineers. Figure 1 shows the destinations of these ultra precision graduates.

In terms of sectors, the students were in high demand and were employed in market sectors including, aerospace, optics and photonics, biomedical, energy, automotive, marine, metrology, precision machining, and manufacturing consultancy.

While the current Centre for Doctoral Training has yet to deliver its first set of graduates, we believe, on the evidence of the successful career progression of the MSc students in Ultra Precision Technologies, there is a strong demand for graduates with an ultra precision engineering focus.

In the Centre, students are admitted to a MRes course at Cambridge and then progress to the PhD programmes at Cambridge, Cranfield, or another UK university through the National Centre Programme of the EPSRC Centre in Ultra Precision. The course we have built has the attributes necessary for delivering a high quality MRes programme. It is also possible for students to take this course as a stand-alone option, without progressing to the PhD, though they would not be able to do this with funding from the Centre. The MRes course is intended to be sustainable and continue beyond the EPSRC funding received so far.

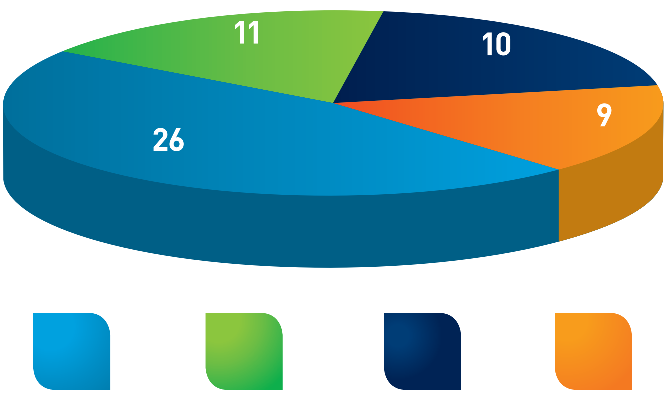


Fig 1: Employment destinations of the MSc in Ultra Precision Technologies graduates

MRes Programme Structure and Requirements

The MRes programme is only offered as a full-time course. The taught course lasts for 11 months (October – August inclusive) and leads to the award of an MRes degree. The students take all of the modules and laboratory classes shown in table 1. In addition, they participate in a group research project and one individual mini research project based (45 credits each) at either Cambridge, Cranfield, or in a collaborating company.

Location	Module Title	Activity	Credits
CRAN	Principles and Application of Precision Machine Design	F	15
CRAN	Advanced Metrology Techniques	F	15
CAM	Energy Beam Micro Processing	F	15
CAM	Display Technologies	C	15
CAM	Management of Technology	B	15
Laboratory Class			
CRAN	Reactive Atom Processing	C	5
CRAN	Optical Test and Measurement	F	5
CAM	Ultra Fast Laser Processing	F	5
CAM	Focused Ion Beam Measuring	F	5
CAM	Roll to Roll Printing	C	5
CRAN	Machine Modal Analysis	F	5
CRAN	Single Point Diamond Machining	C	5

Table 1: MRes taught modules and lab classes

Special innovative features of the programme are as follows:

- All of the staff involved in the presentation of the programme have a strong background in ultra precision systems research and associated subjects, so the course is firmly rooted in up-to-date research practice.
- Teaching is provided by senior figures from both Cambridge and Cranfield Universities, and is supplemented by guest speakers including Prof Richard Leach from the National Physical Laboratory; Prof Chris Evans of the University of North Carolina at Charlotte, Prof Kazuto Yamauchi of Osaka University and Prof Jyoti Mazumder of the University of Michigan. The ability, and indeed requirement, to take courses and laboratory classes across departments in Cambridge and with Cranfield broadens the student experience and widens their perspective of the field in addition to giving them access to world leading precision engineering laboratories.
- Students are required to undertake a fixed collection of modules that deliver to them an educational framework relevant to the study of ultra precision systems. This provides them with the expertise necessary to continue to study at PhD level.
- There is strong collaboration with other Centres for Doctoral Training and Masters programmes both at Cambridge and Cranfield.

- Weekly sessions on transferable skills, particularly those suitable for a research career, allow students to obtain skills that will help them to carry out background study, plan their time and present their results.
- A comprehensive industrial visits programme to showcase best industrial practice in ultra precision engineering included this year visits to the National Physical Laboratory, MSolv, Oxford Instruments, Applied Laser Engineering, Carl Zeiss, and AMSL.
- Attendance at major national and international conferences included this year:
  - International Laser Applications Symposium, Nottingham, UK
  - LAMDAMAP 2013, Kavli Royal Society International Centre, Buckinghamshire, UK
  - Nano Electrical Characterisation Workshop, Coventry, UK
  - Large Area Electronics: addressing the applications challenge, Hauser Forum, Cambridge, UK
  - European Society for Precision Engineering and Nanotechnology Conference, Berlin, Germany
- Participation in the Cambridge Science Festival (http://www.ifm.eng.cam.ac.uk/resources/conference/science-festival/), where the Centre students develop and showcase their ultra precision exhibits to the public. This year's Manufacturing Zone attracted over 2000 members of the public, and has established itself as one of the most popular events of the science festival.

A strong emphasis on learning via mini-projects enables students to gain a deep understanding of particular topics as well as developing background research, analysis, simulation and technical problem solving skills. The requirement to carry out the individual mini-project in different locations, either at the two universities or in industry, further broadens the students' experience and strengthens their research skills.

Individual projects are the main output of the MRes and lead to a thesis, a poster paper and an oral presentation at the yearly research event held by the Centre. Projects are sponsored by company collaborators and align well with the EPSRC Centre in Ultra Precision's research portfolio. The Director of the Centre for Doctoral Training in Ultra Precision, Prof William O'Neill, is also the EPSRC Centre in Ultra Precision's research portfolio manager, ensuring this alignment.

Group projects are an important aspect of the MRes course. These projects are defined to support the creation of the EPSRC Centre's research platforms. Industry interaction is assured through the companies engaged in the realisation of these platforms. Holding the focus of group project topics on to the research platforms also ensures that a number of the MRes trained students can become immediately effective in the research development of the platforms during years 2-4. An example of a group project can be viewed on the EPSRC Centre's YouTube Channel, CranCamUP: http://www.youtube.com/watch?v=KzguWVLyTtQ.

Individual and group projects form 45% of the MRes course. The projects are defined and introduced early during the first term. In so doing, students can consider and develop concepts towards these projects from the outset of their postgraduate experience. In the case of group projects, the longer duration ensures team building and development phases are sufficiently advanced to ensure important deliverables are attained.

Three of the second cohort of MRes students applying their knowledge of machine dynamics to analyse a diamond turning machine in Cranfield's Precision Machine Development Laboratory

First MRes Cohort

We are currently delivering the first cohort of four MRes students who have completed their intensive year of research and transferable skills training, delivered by the EPSRC Centre in Ultra Precision teams at Cranfield and Cambridge. The MRes component requires the students to work on a number of research options, which support the objectives of the EPSRC Centre. A group project entitled 'A Design Study: Laser/FIB machining platform' was completed in May 2013, which laid the foundations of the EPSRC Centre's Nano-FIB research platform outlined on page 8. The four individual research projects that were completed in September 2013 were:

- Femto-second and nano-second pulsed laser machining of carbon nanotubes for field emission applications, Francisco Orozco.
- Spatial light modulators for high laser power applications, Jonathan Parkins.
- Holographic optical fibre, Jiho Han.
- Residual stress measurement using focused ion beam, Rahan Jahromi.

The first cohort of MRes students are currently choosing their PhD topics to start in October 2013. All PhD projects are delivered in collaboration with our industrial collaborators and have received cash contributions to support the work.

Second MRes Cohort

While we are currently completing the first of three cohorts, we have had much success in attracting first-class graduates for our second cohort from a range of disciplines including engineering, materials science, chemistry and physics. In all, 18 applications were received for entry in October 2013. All candidates were interviewed by a panel of researchers from both Universities including Prof William O'Neill, Prof Paul Shore, Prof Daping Chu, Paul Morantz and Dr Martin Sparkes. Offers were made to 10 candidates, with 8 acceptances. The candidates that did not take up the offers took employment in industry instead.

We are attracting extremely high calibre graduates from a wide range of UK universities, including Oxford and Cambridge. It is worth noting that our applicants are sourced from a wide range of academic disciplines highlighting the very broad appeal that the Centre for Doctoral Training is generating from non-engineering disciplines.

We are also seeing high levels of interest from international students. Enquiries already received from self-funded students for entry in 2014 amount to 33% of the EPSRC-funded places, indicating that the Centre brand has struck a chord with international students keen to develop their skills and experience in this area. We believe that once the course has an established reputation the number of self-funded or industrially funded applicants will exceed those funded by the EPSRC, providing a sustainable course that operates beyond the current EPSRC funding limits.

Second MRes cohort 2013-2014

The current student baseline in the first phase of the Centre supports 24 studentships over three cohorts. In our final cohort, we will recruit 12 fully funded UK students and a number of self-funded international students.

Centre for Doctoral Training in Ultra Precision Extension

We have been successful in obtaining admission to the final selection round for further funding from the EPSRC. Panel interviews are being held in late October 2013. In this respect, funding is requested for an additional 4 cohorts of 10 Centre for Doctoral Training students starting in October 2015, bringing the total number of Centre PhD graduates to 64 by the year 2020.

This is a significant increase in the number of highly qualified precision engineers available to the UK industrial and academic arenas that will deliver a step change increase in the number and the calibre of the research outputs and industrial impact of the centre. Moreover, it will provide highly qualified PhD students to other UK universities working in the field of ultra precision in keeping with our National Centre role.

Outlook

The creation of the Centre for Doctoral Training in Ultra Precision has allowed us, in the first instance, to appoint a significant number of prestigious PhD Centre studentships awarded to first-class UK and European applicants. The funding offered by the EPSRC allows the Centre model to develop into an internationally and nationally recognised research and training centre of excellence. Cambridge and Cranfield engineering activities in addition to the EPSRC Centre in Ultra Precision have a wealth of industrial collaborators that are keen to explore this model in order to fast track Cambridge and Cranfield ultra precision engineers into their workforce. We currently have around 24 Centre studentships funded in the first round of training centres.

Given the scale of the problems in ultra precision manufacturing, any increase in these numbers will have a significant impact on the research outputs of the Centre, and the take-up of the ideas by UK industry, providing significant value to many existing and emerging manufacturing sectors.

Quality and Metrics

Initial performance metrics have been proposed in order to monitor the output achievement of the Centre. The table below provides a summary of progress at the end of year 2.

	Target	Achieved at Year 2 point
Publications		
Journal papers 1 paper per 1 research staff person year	55	23
Keynotes given by Centre investigators and researchers 1 keynote given at international conference per 2 staff person years	25	4
Student keynotes /awards 1 student provided keynote or presentation award per 3 staff person years	8	1
Outreach		
Strategic outreach meetings 3 per year to establish Centre as UK hub	15	3
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	2
40% of PhDs to hold RA, engineer or science positions in UK	12	–
Partnerships		
Maintain original partners 75% still active after 5 years	3	3
Engage new industrial partners 2 per year	10	4
Uptake		
Centre main project taken forward by industry	3	1
Centre		
Planning and delivery Hold overall programme by delivering Gantt deliverables and milestones	22	3
Added value to Centre Secure additional funding equal to EPSRC original funding	£6.8m	>£5m

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.

Claverley, J. D. and 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.

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"
Metrologia, 50(4), 354-376.

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"
International Journal of Thermophysics, 32(1-2), 413-426.

Earl, C., Hilton, P. and O'Neill, W. (2012) - "Parameter influence on surfi-sculpt processing efficiency"
Physics Procedia, 39, 327-335.

Fairchild, S., Bulmer, J., Sparkes, M., Boeckl, J., Cahay, M., Back, T., Murray, P., Gruen, G., Lange, M., Lockwood, N., Orozco, F., O'Neill, W., Paulkner, C. and Koziol, K. (2013) - "Field emission from laser cut CNT fibers and films"
Submitted to Journal of Materials Research, paper number JMR-2013-0525.

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. 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, 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.

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.

Leach, R. K., Boyd, R., Burke, T., Danzebrink, H-U., Dirscherl, K., Dziomba, T., Gee, M., Koenders, L., Morazzani, V., Pidduck, A., Roy, D., Unger, W. E. S. and Yacoot, A. (2011). - "The European nanometrology landscape"
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"
Measurement Science and Technology, 23, 074002.

Li, K. and O'Neill, W. (2012) - "Fibre laser microvia drilling and ablation of Si with tuneable pulse shapes"
International Journal of Precision Engineering and Manufacturing, 13, 641-648.

Li, K., Sparkes, M. and O'Neill, W. (2013) - "Improved micromachining of silicon with a pulse shapeable IR fiber laser – a direct performance comparison with the DPSS UV laser"
Submitted to the Journal of Selected Topics in Quantum Electronics, paper number JSTQE-CON-FL2014-04957-2013.

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.

O'Neill, W., Zhang, J., Hu, P., Zhang, R., Wang, X., Yang, B., Wenhu, C. and Xiangdong, H. (2012) - "Soft lithographic processed soluble micropatterns of reduced graphene oxide for water-scale thin film transistors and gas sensors"
Journal of Materials Chemistry, 22, 714-718.

Shore, P. and Morantz, P. (2012) - "Ultra-precision: enabling our future"
Philosophical Transactions of the Royal Society A – Mathematical Physical and Engineering Sciences, 370(1973), 3393-4014.

Tonnellier, X., Howard, K., Morantz, P. and Shore, P. (2011) - "Surface integrity of precision ground fused silica for high power laser applications"
Procedia Engineering, 19, 357-362.

Underwood, R. Davidson, S., Perkin, M., Morantz, P., Sutton, G. and de Podesta, M. (2012) - "Pyknometric volume measurement of a quasispherical resonator"
Metrologia, 49(3), 245-256.

Underwood, R., Flack, D. Morantz, P. Sutton, G., Shore, P. and de Podesta, M. (2011) - "Dimensional characterisation of a quasispherical resonator by microwave and coordinate measurement techniques"
Metrologia, 48(1), 1-15.

Wang, J., Jiang, X., Blunt, L. A., Leach, R. K. and Scott, P. J. (2012) - "Intelligent sampling for the measurement of structured surfaces"
Measurement Science and Technology, 23, 085006.

Prof William O'Neill (left) presenting Krste Pangovski with his CIRP sponsored best presentation award from the EPSRC Manufacturing the Future Conference, September 2013

Conference Publications

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"
SPIE Optifab, 9-12 May 2011, Rochester, USA.

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.

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.

Tonnellier, X., Comley, P., Peng, X.Q. and Shore, P. (2013) - "Robot based sub-aperture polishing for the rapid production of metre-scale optics"
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, 269-278.

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

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.

Appendices

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