EPSRC Centre for innovative manufacturing in ultra precision

EPSRC
Pioneering research and skills

Annual Report

2014 - 2015

Contents

This report was prepared at Cranfield University by the EPSRC Centre for Innovative Manufacture 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, www.light2015.org, NASA, **euspen** Ltd and Vandyke Upper School.

Executive Summary

This report provides an overview of the progress of the EPSRC Centre for Innovative Manufacture in Ultra Precision during its third year. An overview of the complete activities of the Centre is given with detailed information on the key achievements made since the publication of the mid-term report.

The headline goal of the Centre is to better position the UK in securing wealth creation from manufacturing products stemming from inventions in emerging sectors. To facilitate this goal we concentrate on advancing the UK capacity to perform early stage production research by establishing new machines and processing technologies that are demanded for effective production of the key features of emerging sector products.

This precision production engineering focus, whereby future product feature demands are anticipated, has proved well placed. Anticipated component demands have been identified through road mapping events with leading UK researchers and the UK's more innovative technology sectors.

We have been especially pleased that during this third year the specific focus of our Centre has been firmly recognised as being a key EPSRC Grand Challenge for the future, succinctly articulated as engineering across lengths scales, from atoms to applications.

From its onset, success of the Centre was defined as being our ability to reconcile to simultaneous demands of:

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

Our central aim is to produce nanometre scale features and effectively applying them precisely to large scale surfaces in order to realise new products. We have been hugely encouraged by the now widely recognised importance of this topic. The broader recognition of our aim under the "Beyond Moore's Law" thinking firmly supports our focus and central aim.

The numerous UK companies of an SME status that have become central to creation of the Research Platforms has been encouraging during this third year. These machines are the backbone of our research programme. Our research can be considered very much early stage yet it tends to operate along the whole TRL scale and especially so in regards to the UK SME industrial companies with which we engage. This attribute of our Centre is brought about by the necessary machine sub system R&D needed to realise unique research machines.

Creation of these sub systems is recognised by our industrial partners as relatively high TRL. Yet, when brought together they represent British designed and built machines having the potential for world leading ultra precision production capability. The necessary multidisciplinary research will see manufacturing capability readiness levels (MRCL) rapidly advance.

Aside from huge progress in our research we have made significant progress in creating an Ultra Precision Community in the UK. Our events across the whole of the UK have drawn in many new researchers both academic and industrialists. Our network has grown and the popularity of our events increased. This increased attendance is brought about through a greater recognition of the need for ultra precision across a broad product and application range. We'd like to thank all those organisations who have hosted our events.

A long term problem in the UK has been the engineering professions ability to engage the best young people. This problem demands long term and innovative solutions. We believe our Centre has created one such mechanism: Watch It Made®. It gives pre GCSE children (11-13 years old) an experience that conveys two aspects of engineering: excitement of creation and pride of producing. During this third year we have started to roll out delivery of Watch It Made® with over 120 children taking part during the last 6 months. We are delighted to have now secured support from the Royal Academy of Engineering. This high profile support will increase Watch It Made® roll out and translation to a long term business basis.

The Centre for Doctoral Training in Ultra Precision led by Professor Bill O'Neill has proven a huge success and it is now delivering engineering researchers the UK desperately needs to advance capability and capacity. Here again we can see how the prospect of engaging these individuals has resulted in an ability to draw in UK industry. The CDT has significantly broadened the academic partnerships across the Centre and increased its impact potential.

Delivering unique research that realises world leading operational capabilities, evident by high ranking scientific papers and a growing UK industrial take up will be crucial to the Centre's long term sustainability. During the remaining two years under the present funding, the Centre will ensure an effective balance across these critical measures of success. Details given in this 3rd year report will demonstrate our significant achievement thus far.

Paul Shore
Centre Director

National Strategy Programme Development

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

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

The key elements of the National Strategy Programme include:

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

Ultra Precision Website

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

In addition to its own activities, the website advertises worldwide ultra precision events including those of the European Society for Precision Engineering and Nanotechnology (eu**spen**) 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.

In 2014 an Ultra Precision Community page was introduced, dedicated to listing UK businesses that are involved in the field of ultra precision engineering in the supply chain. The purpose of this community page is to provide a shop window to the UK industrial activity in this field and to provide direct contact details for these businesses to interested parties; both suppliers and customers from within and outside of the UK. This activity also allows UK companies to minimise their geographic supply chain by partnering where possible, with local businesses. The aim of this ultra community page is to also 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 Centre's research portfolio shows a series of project portfolios that the Centre's students are engaged in, which link-in directly to the research platforms part of the website where applicable. These portfolios are updated as the student projects progress, ensuring the site is kept as current as possible.

Users may download research outputs from the main research area of the website. Outputs users can view and download include journal and conference publications, reports and outreach presentations. Contributions to this area of the site come from staff within the Centre management team, their colleagues and researchers who are working collaboratively.

The UK database of ultra precision facilities and equipment is an openly available facility 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.

Social Media Engagement

Social media is used to provide news items of interest to the community and to provide updates on upcoming events. 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. 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. The Centre's social media engagement has grown through Facebook (**Ultra Precision UK**) and LinkedIn (**Ultra Precision UK Network**) but notably more via Twitter (**@UPrecisionUK**) with unexpected publicity benefits in many web based journals, blogs and some print media.

Outreach Networking Events

Throughout the year the Centre organised outreach networking events have continued to prove popular and are starting to attract interest from outside the UK, with several overseas visitors and speakers at the last 2 events of 2014. Total number of new businesses, i.e. those that had had no previous contact with the Centre and have connected with its activities via these networking events is now over 40. This is proving an effective way to disseminate the activities of UK industry and to engage industry, particularly SMEs, with each other and with the Centre.

2015 is the International Year of Light and the Centre has registered 3 of its events in the UK programme for these celebrations. It will be co-promoting its events with the Institute of Physics (IoP); the **Prestige Lecture by Prof Gillian Wright**, MBE, FRSE on 31 March 2015 at Cranfield University, **Optical Demands of Astronomy** on 16 June 2015 at the UK Astronomy Technology Centre, Royal Observatory, Edinburgh and **Laser Processes in Ultra Precision Manufacturing** on 15 October 2015 at the Ricoh Arena, Coventry in conjunction with Photonex 2015.

INTERNATIONAL YEAR OF LIGHT 2015

Outreach

External events – the Centre attended since April 2014

Our own events

May 2014

Reel to Reel Road Mapping Workshop

Cranfield University, UK.

The Centre organised a road mapping workshop for the reel to reel technology platform with input from participants from industry and academia in the UK. The aim of the workshop was to identify key industrial drivers and needs; identify which applications are emerging in ultra precision engineering that would benefit from the technological advancements made in the platform; explore the best applications, their value for UK businesses and the best route for their commercialisation and develop a preliminary business plan for the selected applications.

May 2014

National Manufacturing Debate

Cranfield University, UK.

The National Manufacturing Debate hosted by Cranfield University brought together manufacturing professionals from a range of sectors to discuss and debate current challenges in the industry. The Centre exhibited at the event, designed to encourage networking and collaboration across the sector to enable continued and long-term growth.

Delegates were able to take part in tours and demonstrations of Cranfield's impressive facilities and current research, which included a tour of the Centre's facilities within the Precision Engineering Institute.

A range of presentations from keynote speakers were presented, chaired by Lord Alec Broers FREng. The afternoon session commenced with a question and answer session with the Rt Hon David Willetts MP, Minister for Universities and Science, followed by the Debate chaired by Jane Gray, Editor of The Manufacturer.

June 2014

Reel to Reel Production Technology

Swansea, Wales.

This was the Centre's third outreach meeting of 2014 hosted by the Sustainable Product Engineering Centre for Innovative Functional Industrial Coatings Innovation Knowledge Centre (Specific IKC).

The event allowed researchers and industrialists already involved in reel to reel production technology to explain what issues are likely to be and what exists today that could enable early adoption, and what obstacles there may be in establishing production facilities in the UK. The event also included a tour of the IKC's facilities.

June 2014

euspen's 14th International Conference and Exhibition

Dubrovnik, Croatia.

The Centre exhibited at euspen's 14th International Conference and Exhibition in June 2014, Dubrovnik, Croatia. The event offered the possibility to see latest advances in traditional precision engineering fields such as metrology, ultra precision machines and ultra precision manufacturing, assembly processes and motion control in precision systems. Furthermore, new topics were addressed covering precision engineering for medical products and additive manufacturing technologies.

September 2014

3rd Annual EPSRC Manufacturing the Future Conference

Glasgow, Scotland.

The Centre attended the 3rd Annual EPSRC Manufacturing the Future Conference in September 2014, held at the Glasgow Science Centre. This year the conference was hosted by the EPSRC Centre in Continuous Manufacturing and Crystallisation (CMAC). The vision for the conference was to provide a national forum where the community involved in all aspects of manufacturing research, innovation and training in the UK could come together to share experience, progress and challenges in progressing UK manufacturing.

The Centre presented its educational programme Watch it Made®, which was a great success and ideal opportunity to showcase its educational experience.

Wrist watches were designed and assembled in-situ, with delegates having the opportunity to customise their own watch dials with the design or photo of their choice and have the back plate of the watch custom engraved.

November 2014

Micro Surface Structuring

St Asaph, Wales.

The Centre's last outreach meeting of 2014 was at the OpTIC Centre, St Asaph, Wales in November hosted by Ultra Precision Structured Surfaces (UPS²).

The meeting brought together some of the UK's exponents in the micro surface structuring field to discuss the methods of production and some of the industries that are starting to see applications for this technology. The event was aimed at updating and connecting UK business and academia in these fields and to show some of the world-class technologies and processes that are being developed here in the UK. The day also included laboratory tours of UPS².

November 2014

Precisiebeurs 2014

Veldhoven, The Netherlands.

The Centre exhibited at the annual Precisiebeurs 2014 (Precision Fair 2014) exhibition held at the NH Conference Centre Koningshof, Veldhoven, as part of a UK cluster exhibition stand. UK companies that joined the Centre included Elecktron Technology, M-Solv Ltd and Loxham Precision.

The fair included a two day lecture programme. The Centre's National Strategy Manager, Martin O'Hara presented the activities of the Centre on day one and on day two a presentation entitled *'What is ultra precision?'* as part of an afternoon of lectures chaired by eu**spen**.

February 2015

Micro Manufacturing

The Manufacturing Technology Centre, Coventry, UK.

This event was the Centre's first outreach meeting of 2015 held in conjunction with eu**spen**.

The meeting was intended to attract the UK's top practitioners, industrialists and academics in the field of production and machining of micron or smaller sized features. The application of these features at small dimensions are varied, including security tagging, hologram reproduction, ultra precision component parts for micro machinery, optical gratings and a myriad of other functions that might at first glance not be so obvious in daily use, but rely on these small scale micro manufacturing practices to enable much of modern life to exist.

There were nine presentations given from industry and academia and delegates were also given the opportunity to view the MTC's facilities as part of the tours organised throughout the day.

"The Ultra Precision networking event in February 2014 at CPI brought together industry and academic experts and enabled us to showcase our facilities. Several interesting projects from the event are being considered and we are now working together with the Ultra Precision and Advanced Metrology Centres to develop a roll to roll summer school for 2015. This has strengthened the relationship between CPI and the Ultra Precision Centre and we look forward to a very productive relationship moving forward."

Dr. Jon Helliwell, Director of Printable Electronics, Centre for Process Innovation

April 2014

Top: Watch it Made® Group Project Team **Bottom:** UP Diamond Machining System Group Project Team

MSc Group Project Presentation Day

Cranfield University, UK.

Cranfield University's MSc Group Project Presentation Day took place in April 2014, showcasing projects from the Manufacturing and Materials Department.

Projects were presented in a multi-track event covering design, manufacturing and materials related research. Students spent three months working full time in groups delivering on strategic projects, many supported from industry. The presentation day provided an opportunity for the students to demonstrate the value that they have brought to sponsoring clients as well as an opportunity for networking.

Projects sponsored by the EPSRC Centre in Ultra Precision were presented; Design and Build of an Ultra Precision Diamond Machining System and Watch it Made®.

June 2014

Work experience student with Precision Engineering Institute technical staff and Dr Paul Comley (right)

Work Experience Placement

Cranfield University, UK.

A GCSE student from Redbourne Upper School, Ampthill, Bedfordshire, spent a week at Cranfield in June 2014 undertaking work experience within the Precision Engineering Institute. During her stay she worked with MSc students on the Watch it Made® Educational Demonstrator Programme, undertaking a machine evaluation study. Other activities included simple CNC programming and operation of a CNC lathe, diamond turning, and metrology using co-ordinate measuring machines and surface texture instruments.

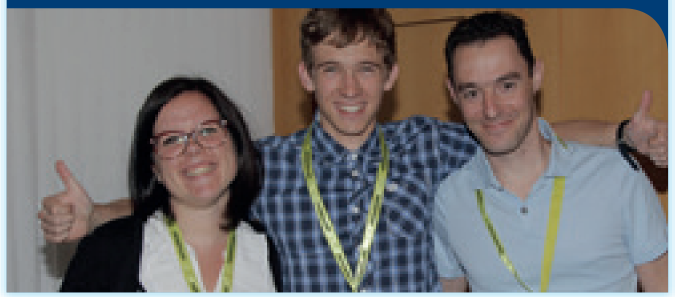
July 2014

euspen Challenge 2014

Traunreut, Germany.

eu**spen** Challenge is an annual international competition held by eu**spen** Limited, identifying students with potential to be future leaders in the field of precision engineering and nanotechnology. euspen and Heidenhain GmbH hosted thirty European and international students in Traunreut, Germany. Working in culturally diverse teams, the students benefitted from national and international teamwork exposure, engineering and business skills development, professional networking and the unique opportunity to connect with leading companies in this field.

PhD researchers Jonathan Abir, Nan Yu and Karen Yu, represented Cranfield and Cambridge Universities in the euspen Challenge 2014. Jonathan was part of winning Team Hertz who were awarded the Best Presentation and Most Innovative Solution.



Team Hertz with the Centre's Jonathan Abir (right)

2014-2015

Engaging with Local Schools

Bedfordshire, UK.

The Centre's Director, Professor Paul Shore, visited various schools in Bedfordshire throughout 2014 and 2015 to deliver his lecture *'Engineering or Super Heroes?'* One such school was Vandyke Upper School based in Leighton Buzzard, Bedfordshire where he presented to talented scientists in Years 10 and 11, as part of the school's programme for potential high achievers.

Paul showed the students the many practical applications of physics and engineering; bringing in titanium hip and finger joints, £50,000 mirrors used in the most advanced telescopes and tiny globules in which elements are stored to create nuclear fusion.

Students and staff left the sessions with their brains still bursting with questions and wondering about the concepts to which they had just been exposed. One student said, "It helped you to learn physics in a way that you didn't even realise, very enjoyable and fascinating." Another commented, "It was interesting that there is so much to do in engineering science and how in that field science-fiction is becoming science fact."

The school thought it was a great experience, both as an insight into the relationship between the school curriculum and its wider application and as a way of broadening students' awareness of career opportunities open to them in the future.

Other schools where this lecture was presented were Kimberley STEM College based in Stewartby, Bedfordshire and UTC Central Bedfordshire based in Houghton Regis, Bedfordshire.

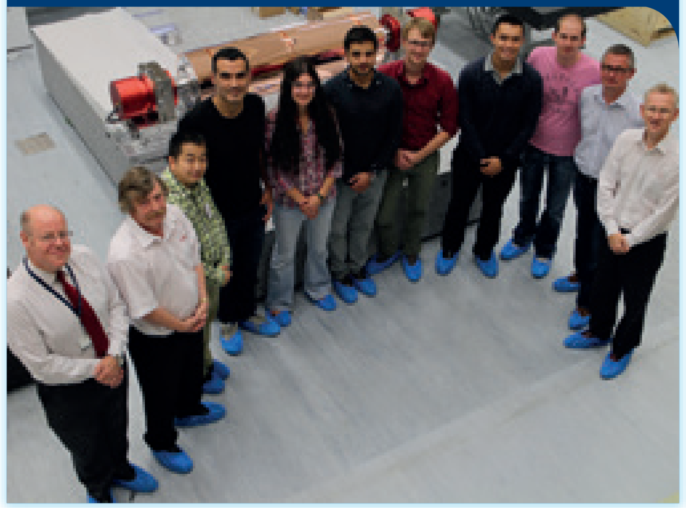
Prof Paul Shore with staff and students of Vandyke Upper School

September 2014

Precision Engineering Industrial Short Course

Cranfield University, UK.

The Centre's annual Precision Engineering Industrial Short Course took place in September 2014. This was a five day practical, results orientated short course for engineers in the machine tool, automotive, aerospace, optics and semiconductor industries. Delegates that attended were from FANUC UK, Aerotech Ltd, Professional Instruments Company (USA), Hembrug Machine Tools (The Netherlands), CERN (Switzerland), Ideko (Spain) and NSK Ltd (Japan). Guest lecturers were Hans Vermeulen of ASML, The Netherlands and Richard May-Miller of Cranfield Precision.



2014 short course cohort with the Centre's Paul Morantz (left) and Prof Paul Shore (right)

January 2015

Centre Research Portfolio Presentations

Institute for Manufacturing, Cambridge, UK.

The Centre organised an evening event where all of the PhD researchers presented an overview of their research projects to members of the Centre's steering group and Chairman. Local SMEs were invited and the event also provided networking opportunities and for students to further showcase their projects with poster presentations.

Watch it Made®

Watch it Made® is the Centre's educational programme conceived by Cranfield University staff who wished to create an engineering activity that would make young learners experience the unique "pride of producing" that only engineering can offer, and to enthuse children into science, technology, engineering and mathematical subjects prior to their GCSE subject selections.

The Watch it Made® experience is given in a dedicated Manufacturing Learning Studio based within the Precision Engineering Institute at Cranfield University. Initially children spend time choosing the design of their watch face dial and see how it is printed using a UV ink jet technology. They then get hands on experience mounting their watch case in a precision lathe, operating it, and seeing their watch body machined. Thereafter, they personalise the watch rear cover using a micro-milling process. Finally, the children assemble all of their manufactured watch components, together with some pre-supplied parts e.g. hands, watch glass and strap. At the end of the session, all of the children leave with their own personalised timepiece.

The experience was created by two MSc group projects supervised by Cranfield University. Florian Caroff and Armand Didier were part of the second group project who defined the content of the Watch it Made® experience and designed a watch that could be assembled by children. They also proved the fun learning experience that children obtain when they use modern engineering design and manufacturing to make a self-designed quality watch.

Following their MSc group project, Florian and Armand decided to advance the Watch it Made® experience. Florian investigated and defined the modern machinery necessary for children to make watch components and Armand designed simple to use tooling that enables children to easily and safely assemble their own watch. At the end of their MSc studies, Florian and Armand decided to further pursue the Watch it Made® activity and now plan to launch a spin out company, incubated within the EPSRC Centre for Innovative Manufacturing in Ultra Precision at Cranfield University.

Watch it Made® was launched at the 3rd Annual EPSRC Manufacturing the Future Conference in Glasgow, September 2014. To date, it has hosted over 100 experiences for children of Cranfield University staff and welcomed local schools Samuel Whitbread Academy, Arnold Academy, Goldington Academy, Bedford Modern School, Bushfield School, Hastingsbury Business & Enterprise College, Holywell School and Biddenham International School & Sports College.

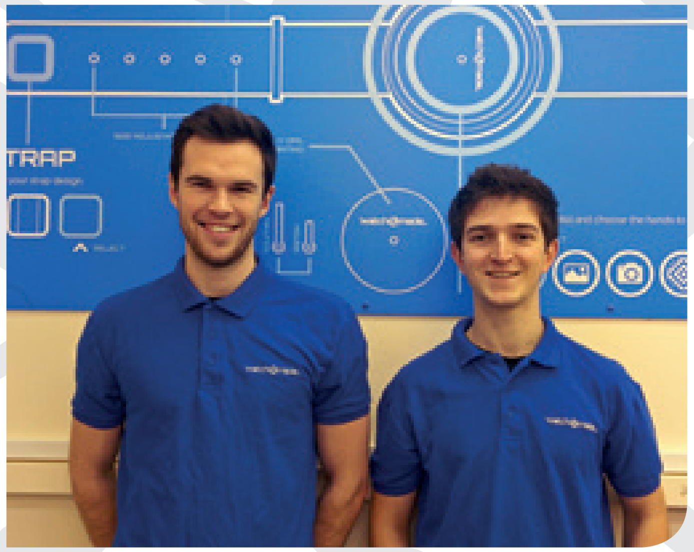
To find out more about Watch it Made®, please visit

www.watchitmade.org

"I LEARNED HOW TO MAKE A WATCH AND THAT I LIKE ENGINEERING"

Prof Raj Roy, Director of Manufacturing at Cranfield University with the Watch it Made® team and pupils of Bedford Modern School

"I LEARNED ALL ABOUT DESIGNING AND PRODUCING A WATCH AND HOW MUCH I LOVE CREATIVE WORKSHOPS."



Watch it Made® leaders Florian Caroff and Armand Didier

Watch it Made® team with pupils of Hastingsbury Business & Enterprise College, Bedfordshire

"THE BEST PART OF THE DAY WAS WATCHING THE ENGRAVING AND THE FEELING WHEN THE WATCH WAS FINISHED."

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

Amy Camfield, Head of Science, Goldington Academy.

"I am very impressed with this product and the outreach activity attached to it. The watch keeps perfect time and I show it off to everyone that I meet. It goes without saying that they all want one. It is surprisingly comfortable to wear and one of the most amazing features is that it fits me and my 4 year old daughter. She thinks it's very special with her photo on it and she has learned to tell the time (to the hour anyway) in the 4 days that she's had it."

Dr Peter Schubel, EPSRC Centre in Composites, University of Nottingham.

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

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

"The whole day was a fantastic opportunity for our students. They loved designing and making their watch, talking to the staff, taking photos and their tour. We had a brilliant time. Thank you very much."

Miss McDonnell, Biddenham School.

Further Outreach Activities

The Centre's National Strategy Manager, Martin O'Hara continued to be active in attending various one day meetings and events which included **Micro and Nano Fabrication of Next Generation Technologies** (Rutherford Appleton Laboratory, Harlow), **Photonex Technology Roadshow** (Cambridge), **Plasma Quest Ltd** (Hampshire) and **Oxford Instruments Plasma Technology** (Bristol), **CERN Experiments in the UK: Meet the Buyer** (Royal College of Physicians, London), **Electronics Design Show** (Ricoh Arena, Coventry), **Innovation in Large Area Electronics Conference (InnoLAE) 2015** (Cambridge), **Nikon Metrology Open Day** (Derby) and supported M-Solv Ltd at their **Thin Flexible Glass Exhibition and Open Day** in Kiddlington, Oxford.

Martin presented the Centre's activities at the **Engineering Employers Federation (EEF)**, **East of England Regional Advisory Board** (Cambourne, Cambridgeshire) and at **Photonex 2014** (Ricoh Arena, Coventry), where the Centre also had an exhibition booth.

Exchange visits were made with **Abbey Precision** (Milton Keynes), a local supplier of parts to the Watch it Made® programme.

Martin participated in a **European Measurement Programme (EMPIR)** submission for highly parallel manufacturing, held in Berlin, using the reel to reel platform as a test bed for future measurement standard and instrumentation development by European National Measurement Institutes (NMI's), led by the National Physical Laboratory. The project bid was successful and is due to commence early 2015.

Reciprocal visits were made with **Double-R Group** (Heywood, Lancashire) and the Centre hosted visits from **Enterprise Europe** (East of England), **ITL Vacuum Components** (Hastings), **DMP Aero** (Spain), **Lein Applied Diagnostics** (Reading), **Compound Photonics** (Newton Aycliffe), **National Physical Laboratory** (Teddington), industrial visitors who attended Cranfield's **Industrial Engagement Day** and the **EPSRC Centre for Innovative Manufacturing in Liquid Metal Engineering** (Brunel University London).

International Collaborations

The PACMAN project, Particle Accelerator Component Metrology and Alignment to the Nanometre scale has been created by the **European Organisation for Nuclear Research (CERN)** within the study for the Compact Linear Collider (CLIC) due to the very tight error budget of this project. It is an innovative multidisciplinary programme funded by the European Committee aiming at training 10 PhD students.

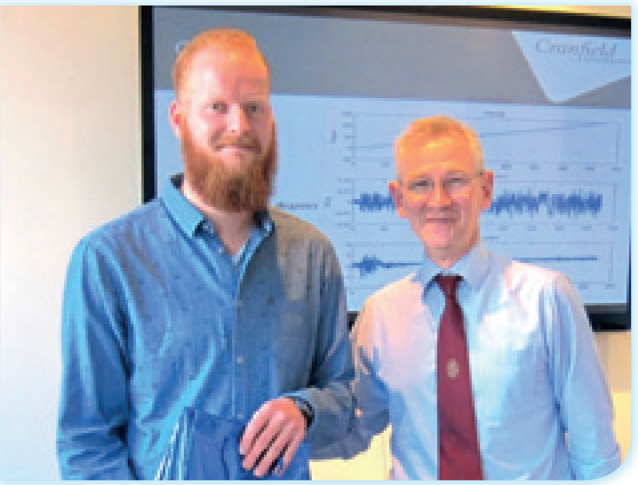
The Precision Engineering Institute at Cranfield University is supervising two Early Stage Researchers who are part of this PACMAN consortium: **Miss Claude Sanz** and **Mr Iordan Doytchinov**.

The Centre hosted **Rens Samplonius**, a MSc degree student of **Eindhoven University of Technology** for three months as an intern researcher working on the polishing of large optical components using a robot.

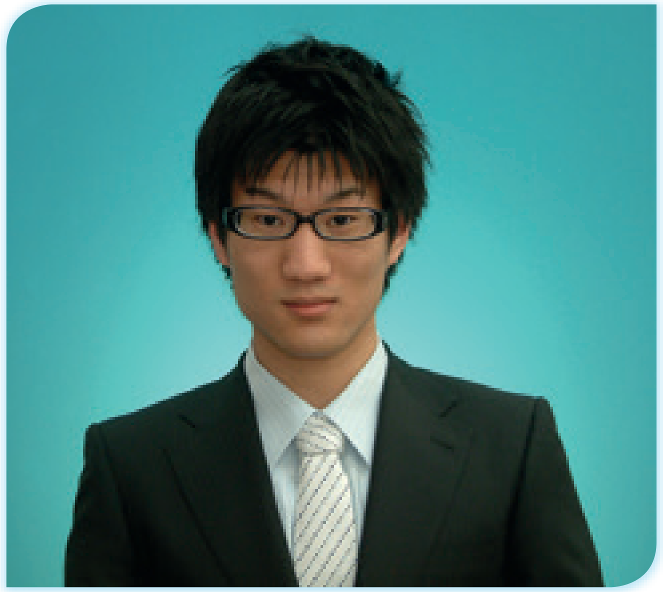
An industrial robot based polishing system has been developed at Cranfield using a Fanuc M710IC/50 6-axis robot, aimed at bridging the asphierisation and final figure correction processes. The use of conventional industrial robots is a low capital cost alternative compared to conventional high cost sub-aperture polishing systems, offering the potential to employ higher numbers of low cost units within manufacturing cells.

The goal of this project was to enhance this existing industrial robotic polishing platform by fitting an additional rotary axis. This aimed to improve the polishing efficiency by using a spiral rather than a raster tool path for optical glass/ceramic components.

The outcome of this project saw the successful design, assembly and control for this hydrostatic rotary axis. Polishing experiments were carried out on a CVC silicon carbide specimen using polycrystalline 3 μm diamonds. An average removal rate of 0.133mm3/min was achieved with a surface roughness (Ra) of 41 nm. The results demonstrate that a spiral tool path is a more efficient polishing strategy than raster polishing on silicon carbide surfaces.



Rens Samplonius (left) with Prof Paul Shore



Yoshinori Takei

Visiting researcher **Yoshinori Takei (Yoshi)** from the **University of Tokyo** undertook an international six month placement at Cranfield University from June 2014 to January 2015. He performed a detailed verification analysis of Cranfield's large mirror optical test measurement tower.

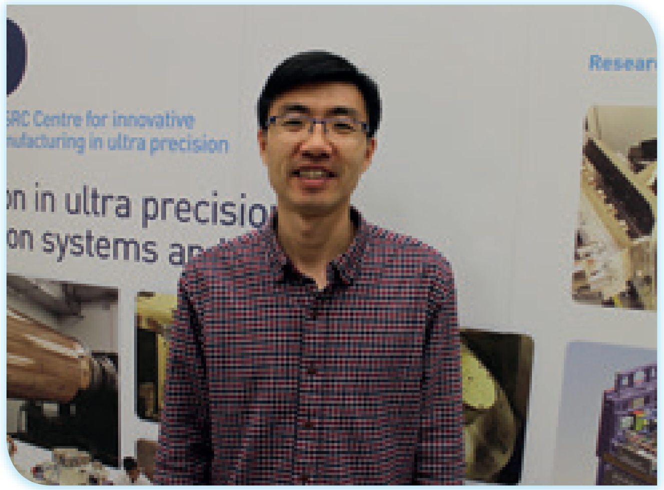
Through carefully designed performance testing Yoshi was able to demonstrate the Cranfield test tower had a 1 nm RMS reproducibility level when measuring 400mm size optical surfaces.

This excellent metrology research was presented at the eu**spen** Special Interest Group meeting on Structured and Freeform Surfaces which was held in Padua, Italy in November 2014. These results were welcomed by UK company Lambda Photometrics who will use the data to validate performance of interferometers they supply.

In February 2015 after his return to Tokyo, Takei Sen presented his Cranfield based research at the Annual Conference of the Japanese Society of Precision Engineering (JSPE).

Dr Lin Zhang, Assistant Professor and Graduate Tutor of **Nanjing University of Aeronautics and Astronautics, P. R. China** is a visiting academic within the Precision Engineering Institute at Cranfield University. During his time at Cranfield, he will be undertaking research in ultra-precision continuous film processing, which includes several key technologies including diamond ultra-precision turning, electroless nickel coating technology, grating machining technology and the replication technology onto film using FIB tools.

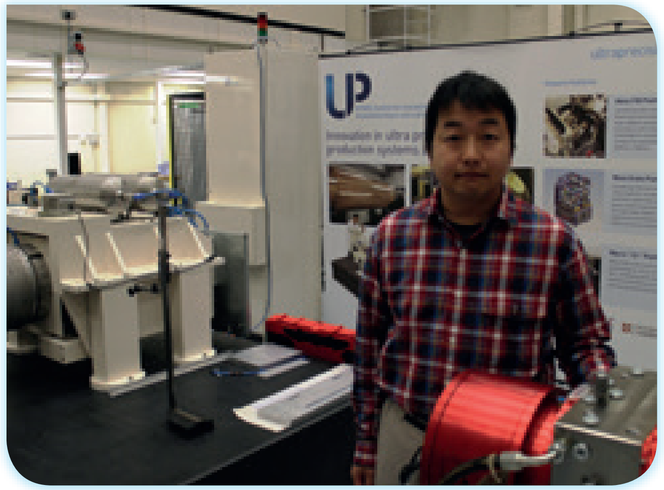
Dr Zhang has been working for six years in College of Mechanical and Electrical Engineering at Nanjing University of Aeronautics and Astronautics. His research interests are CNC machine tool system design and optimization, micro machining technology, aircraft flexible assembly technology and industry robots. To date he has published fifteen papers two patents of invention.



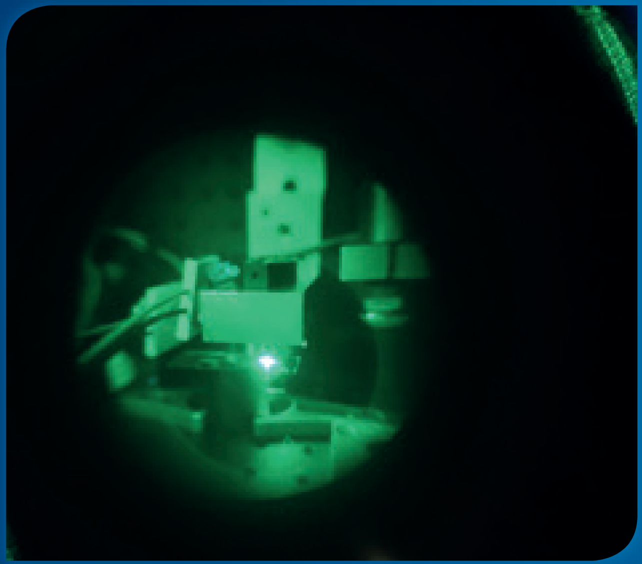
Dr Lin Zhang

The Centre is hosting **Mr Takashi Yoshimura** of **NSK Ltd, Japan**, a visiting academic within the Precision Engineering Institute at Cranfield University. Takashi's research will focus on the development of a reel to reel bearing system for the Centre's reel to reel platform.

Takashi has been working for NSK Ltd, a Japanese bearing manufacturer for over 10 years. His speciality is numerical analysis, and he has designed grinding spindles for their bearing manufacturing process.



Takashi Yoshimura



Future Outreach Events

The Centre will be exhibiting at the **National Manufacturing Debate** in May 2015, which is an annual event hosted by Cranfield University. In June 2015, the Centre plans to exhibit at **euspen's 15th International Conference and Exhibition**, Leuven, Belgium with the aim of collaborating with UK SMEs to exhibit as a UK cluster stand. The Centre will be adopting the same principle for **Precisiebeurs 2015**, in November 2015, an annual event held in Veldhoven, The Netherlands.

The **4th Annual EPSRC Manufacturing the Future Conference** to be held at Churchill College, Cambridge, 17-18 September 2015, presents the latest manufacturing research delivered by the academic community in collaboration with UK industry. Sponsored by the EPSRC's Manufacturing the Future Theme, the objective is to provide a forum through which academic and industrial communities engaged in manufacturing research, development and implementation can meet to present their latest research outputs, share their ideas, exchange best practice and discuss topics of importance to the community. The overall aim being to further develop the UK's position in high value and high impact manufacturing research.

The conference will be open to invited representatives from academia and industry. Academic delegates will include key representatives from the EPSRC Centres for Innovative Manufacturing, other current Manufacturing related EPSRC Centre grant holders, EPSRC Manufacturing Fellows, Centres for Doctoral Training and EngD Centres. Industrial delegates will include leading decision makers and representatives from UK industry, Innovate UK sponsored activities, the High Value Manufacturing Catapults and EPSRC/Catapult Research Fellows.

Presentations will be both academic and industrial, with a UK and international focus. Networking opportunities through this event will be enabled by a conference dinner at Duxford Aerodrome, exhibition, poster sessions and break-out sessions designed to exchange ideas within the community.

Centre outreach events planned for the remainder of 2015 include a **Prestige Lecture "James Webb Space Telescope"** by Prof Gillian Wright MBE, FRSE, Director of the UK Astronomy Technology Centre, Edinburgh at Cranfield University, March 2015; **Optical Demands of Astronomy** at the UK Astronomy Technology Centre, Edinburgh, June 2015 and **Laser Processes in Ultra Precision Manufacturing** at the Ricoh Arena, Coventry, October 2015. The Centre will also deliver its annual **Precision Engineering Industrial Short Course** at Cranfield in September 2015.

The **EPSRC Centre for Doctoral Training in Ultra Precision Conference & Exhibition** will take place on 12 May 2015 at the Institute for Manufacturing, University of Cambridge. This one day conference and exhibition will showcase advances in ultra precision engineering in fields such as additive manufacturing, nano and micro manufacturing, metrology, mechatronic systems and control, and ultra precision machines. The event is designed to provide an opportunity for industrialists and academic researchers to share their latest ideas and to explore future collaborative opportunities in the field of ultra precision engineering.

Sustainability

Participation at Precisiebeurs 2014 (Precision Fair 2014), The Netherlands was a test bed for one of the Centre's post funding sustainability initiatives. The Centre took three small UK businesses to this international fair as part of a UK precision cluster stand. This sustainability model will be taken forward in 2015 to other overseas exhibitions with other UK businesses that are part of the ultra precision community.

Presentations

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

Abir, J., Morantz, P. and Shore, P. *'Bottom-up modal analysis of a small size machine tool' (poster presentation)*
3rd Annual EPSRC Manufacturing the Future Conference, 23-24 September 2014, Glasgow, UK.

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

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

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

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

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

Yu, N. *'Analysis of nozzle design used for reducing the MSF errors in rapid plasma figuring' (poster presentation)*
3rd Annual EPSRC Manufacturing the Future Conference, 23-24 September 2014, Glasgow, UK.

Keynote Lectures

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

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

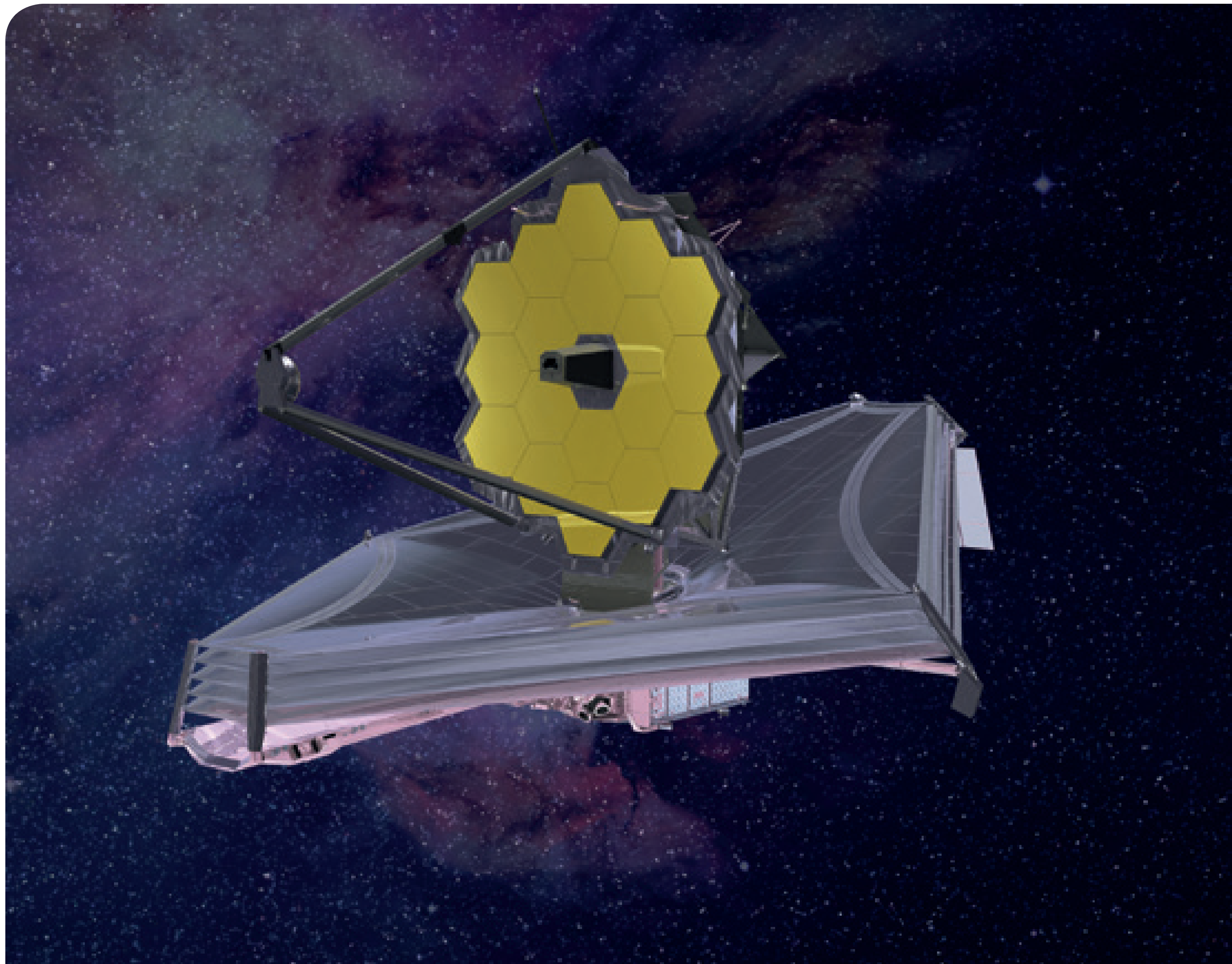
Leach, R. *'On-line surface metrology challenges'*
International Symposium on Precision Engineering Measurements and Instrumentation (ISPEME 2014), 8-11 August 2014, Changsha, China.

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

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

O'Neill, W. *'Additive manufacturing, a technology set for change?'*
The International Laser Applications Symposium 2015, 17-18 March 2015, Kenilworth, UK.

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



Research Platforms

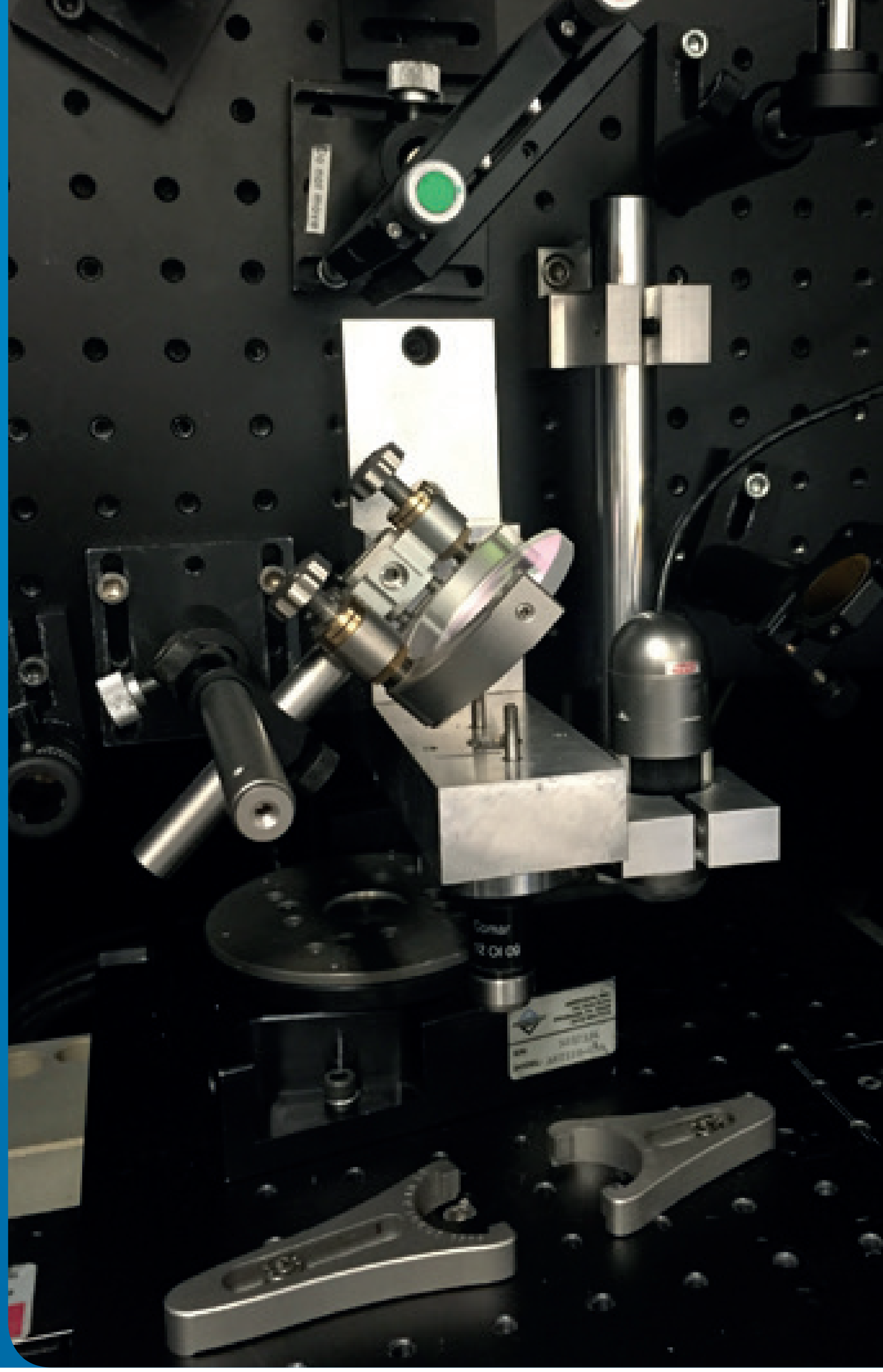
Laser FIB Platform

The laser focused ion beam (FIB) platform is being developed to provide an ultra precision device production platform capable of offering micro and nano-machining capabilities with integrated metrology capabilities for a wide range of materials utilising an integration of laser and focused ion beam technologies. The design brief requires length scale machining resolutions for the two principle processing routes at 30nm for the focused ion beam (FIB) and 200nm for the laser processing approach.

Ultra precision processing requires advanced metrology solutions in order to deliver a 'right first time' production capability. In this respect a number projects delivered through the research portfolio have provided the laser system with an on-board laser focus control system in addition to a single point Optical Coherence Tomographic depth measurement system. The metrology tool-set will be complete once the large area holographic microscope capability is incorporated in the summer of 2015.

The Ga based focused ion beam machining studies were completed early in the project. These included process resolution limits for a range of materials, and methods of eliminating Ga ion impregnation, a common problem in Ga based FIB processing.

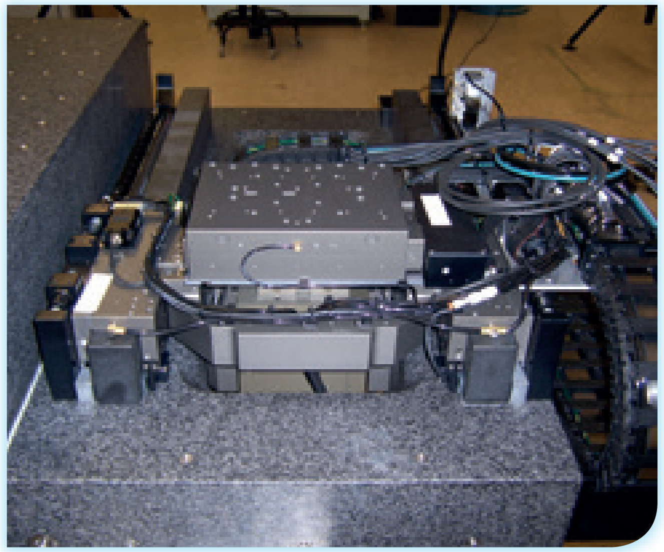
Ultra precision process research is now concentrating on developing the integrated processing steps for hybrid laser and FIB precision machining. These include the design and production of precision pallets for work piece handling in both the laser and FIB processing domains. In addition, the control and software architecture for supporting the hybrid processing is under development with the support of the industrial sponsors at Zeiss.



The laser FIB platform is in the closing stages of development. The past year has delivered the detail design concepts of the laser focused ion beam production route and the overall system is currently in production and due for completion in May 2015. Much effort has been applied to the laser side of the platform, with the aim to deliver a nanoscale production system with integrated metrology that will allow the fabrication of devices with nanoscale precision.

The laser FIB platform consists of an integrated motion system that offers 5-axis positioning with a resolution of 50nm and positioning stability of 25nm. A complex optical beam train with multi-wavelength capabilities is mounted on a bespoke granite bed designed to offer exception stability.

Due to the variation of processing methodologies employed, the system is capable of delivering single point laser processing, fast galvanometric scanning and large area holographic imaging utilising a LiCoS phased array mirror. Multiple laser systems are incorporated including an Amplitude Systèmes femtosecond fibre laser at 300 fs pulse width (500 kHz) and 10 µJ pulse energy, in addition to a Coherent Talisker picosecond laser at 50 µJ (1 MHz) pulse energy and wavelengths of 1 µm (20 W), 532 nm (10 W) and 355 nm (5 W). These combined systems offer substantial processing capabilities on a wide range of materials, in addition to delivering process resolutions of around 200nm using discrete ablation level control techniques that have been developed within the research portfolio programme.



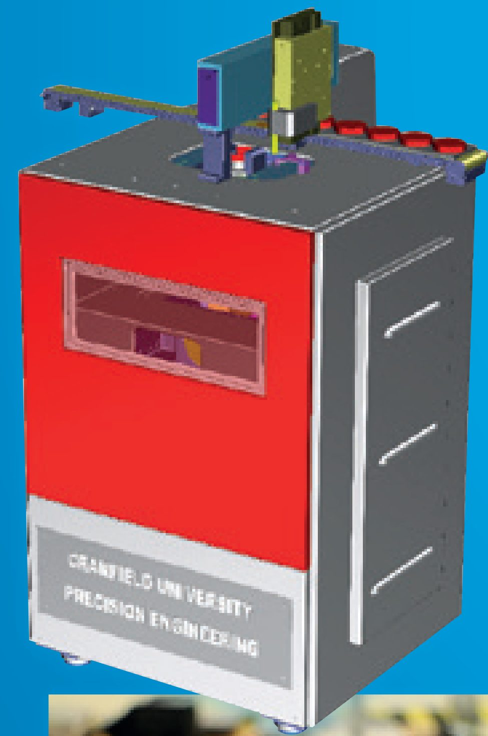
The plan to implement He/Ne ion processing was disregarded due to the financial constraints within the platform budgets. Whilst this is a setback in turns of ultimate processing resolutions, the laser FIB processing routes can still be validated with Ga ion machining, albeit with process resolutions of 30nm rather than 5nm. The laser system should be able to quickly and accurately add or remove material from a sample wafer, so that FIB machining can be used to finish the process with very high accuracy. Because a laser can remove material far faster than a FIB, relatively large structures can be completed with FIB accuracy using this method, in a fraction of the time when using the FIB alone. The new laser FIB technology components will be in place by May 2015 and applications trials for a number of project partners will be underway in the summer of 2015.

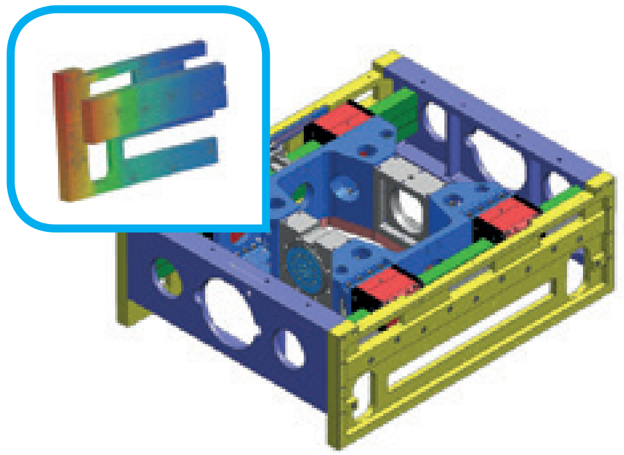
Meso Platform

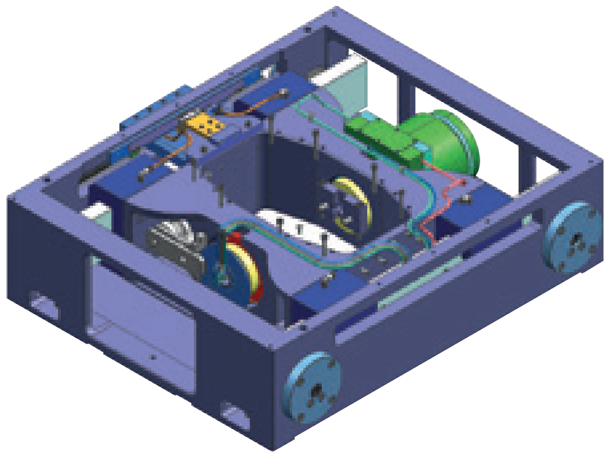
The meso platform is a novel research system that challenges a number of the typical machine tool conventions. It is specified at a leading performance for an ultra precision diamond machining system, yet it is also specified to be highly integrated, compact and configured to have low energy consumption.

The process technologies will include: single point diamond turning, micro milling and drilling. In subsequent years, the Centre's concentration will be given to incorporation of micro embossing, nano imprinting and micro stamping processes.

The target "accuracy and productivity performance" for the meso machine has been set at the level of the highest performing traditional ultra precision diamond turning machines, typically 1-10 nm Sa surface roughness levels and form accuracy in the sub 50 nm RMS region. Traditional machines are typical 10 times larger by volume and consume many times more energy than the meso platform machine. The meso platform will verify both highly integrated mechatronics with verified portability of machine tools having white goods product size.







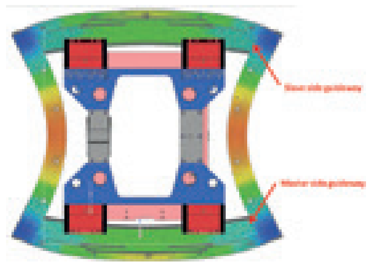
Meso Structure Optimisation

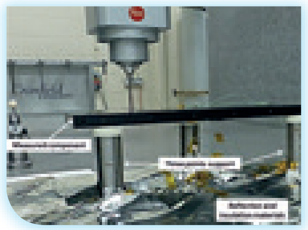
During this third year the meso scale machine concept has progressed with regards to structure optimisation. The original meso machine structure was based around a lightweight aluminium bolted plate structure. Its performance was found to be difficult to implement without notable in fabrication and in assembly measurement. Furthermore, relatively minor thermal variations were found to have a notable impact on the motional performance of the air bearing slideways.

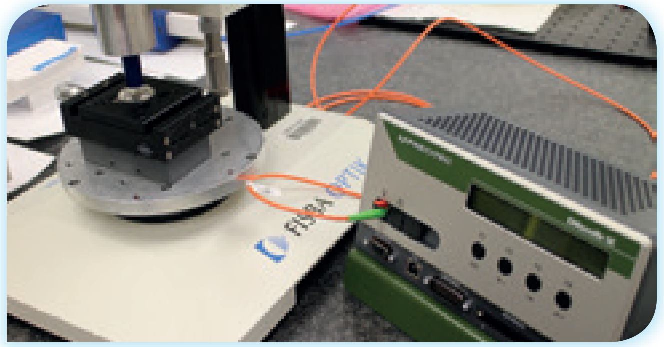
In the Centre's second year, a student project created a new ultra precision diamond machining system to improve the accuracy of the plate structure. Whilst this new system improved the geometry of the bolted structures, thermal distortion in a changing environment remained a significant issue. During this third year new structural designs have been created based on casting concepts. This work has been translated through a Cranfield University spin out company, Loxham Precision. It is recommended the final meso platform will employ both aluminium castings and slideway bearing structural elements.

Thermal Distortion Analysis

In order to research and to validate any non reversible distortion characteristics of the bolted plate and the ceramic air bearing rail design, CMM based measurements were performed. These measurements were carried out after applying thermal loads of differing magnitude. The thermal loads were applied using spot lamp heat sources. This work by Jonathan Abir was reported in depth at the Lamdamap 2015 conference. The results have already been used to refine the design specification for the meso platform.







In-Situ Metrology

Measuring shape accuracy of components within the meso machine has been identified as a means to maximise productivity and avoid additional handling. Whilst in-situ workpiece metrology offers advantages in both these aspects it can prove uneconomic if the measurement cycle times are significant. Through an aligned Innovate UK project involving Hexagon Metrology, a new confocal probe system has been provided to support integration development of the meso platform. Work is now planned to perform measurement operations on various optical surfaces. These will include aspheres, free forms and finely structured features. This measurement system research could have applicability to the reel to reel platform metrology system development.

Reel to Reel Platform

The reel to reel platform is a research system that will create and advance production techniques for realising effective fine feature creation onto large scale flexible films with high accuracy and rapid processing rates.

The processing capabilities will include: application of epoxy films, large scale micro-feature embossing and UV cure polymerisation, in processing film metrology and alignment, laser machining, ink jet printing and precision lamination.

The target "accuracy – areal size – production capacity" has been set at an order of magnitude greater than can be achieved using available machinery.

During this third year the reel to reel research platform has progressed in a number of key areas.

Advanced Hydrostatic Roll Motion Unit

UK companies / partners: Castech Ltd, Poeton Ltd, Renishaw, 3D Evolution

Motion control of the embossing technology has been advanced through the design and build of specially conceived hydrostatic roll motion units. The design of these spindles has enabled a number of UK companies to form an effective high precision spindle manufacturing supply chain. Use of advanced coatings technologies, easily processed materials and diamond machining techniques have tremendously reduced the cost and complexity of producing these high accuracy low friction precision motion devices.

Large Scale Embossing Technology

UK Companies / partners: UPS², Keating Specialist Cylinders Ltd

During the second year, activities had already taken place with regard to fabrication of large scale embossing rolls. This ultra-precise fabrication activity is based around a unique UK manufacturing supply chain for producing micro-structured rolls. This UK capability was first conceived through the EPSRC funded UPS² Integrated Knowledge Centre. UK designed and produced rolls are being employed within the reel to reel platform.

In this third year a method for precisely locating and instrumenting large scale films has been conceptualised and validated. The technique involves embossing Moire fringe gratings into the films as a first step of an instrumented reel to reel process. To introduce the grating features onto the film it was necessary to create large scale rolls having gratings cut into the drum surface. A first test roll was produced by UPS² in North Wales. This drum has 6 gratings that provide potential for lateral, circumferential, tilt and film distortion measurement capabilities. Hand crafted film replicas have proven good transfer fidelity and measurement functionality.

UV Polymerisation for Effective Creation of Micro-Bossed Features

UK companies / partners: UV Integration, iXscient Ltd, Microsharp

This technology has been researched in partnership with UK companies iXscient Ltd and Microsharp. After critical testing and validation studies a high specification LED based UV curing system was defined. This 1.5 metre wide programmable UV light system having 20kW power capacity at 365 nm was designed and produced by UK company UV Integration. This programmable system is capable of delivering 7W/cm² providing a curing capability range of 1 – 10 metres per metre. This UV system was delivered in February 2015.

Temperature Control Advancements

UK companies / partners: 3DE, Loxham Precision Ltd

Applying a powerful UV light source to achieve a rapid polymerisation capability brings about undesired thermal distortion concerns. Therefore, two other UK companies who specialise in temperature control technologies, 3DE and Loxham Precision, were engaged to devise and deliver flexible low energy consuming temperature control systems.

Stray energy is an enemy of precision engineering, therefore to ensure the main precision spindle motion systems of the reel to reel platform and the embossing drum itself are not unduly affected by the local heat source, temperature control units of a specialist design were defined by Loxham Precision (a Cranfield spin out company) and produced by 3DE. These units offer milli Kelvin resolution temperature control.

Wet UV Lacquer Application System

In order to establish a means to apply finely controlled wet UV lacquers to films, process studies were carried out in association with iXscient and Microsharp. The achievable performance of differing wet lacquer coating methods was considered against a leading reel to reel specification. This leading specification derived a capability of applying wet films as thin as 0.5 micrometres and as thick as 100 micrometres. Processing speed of coating was set at 1 – 20 metre per minute for lacquers of viscosity range 50 – 3000 mPas. At this level of performance only the slot die coating technology would be viable.

Slot Die Supplier Process

Acquisition of the slot die technology was necessary and no obvious UK supplier could be found. As the investment was likely to be over £200,000 a full EU open purchase process was followed. Three international bidders were secured from the US, Germany and Switzerland. The winning supplier was TE Troller of Switzerland. This system is due for delivery in August 2015.

"I am impressed and extremely interested in your reel to reel system and welcome the opportunity of being involved. We are a British company manufacturing reel to reel equipment and have extensive experience in many of the processes, access to a large-scale research platform will help keep the UK ahead in this technology."

Neal Rothwell, Group CEO, Double-R Group

The Research Portfolio

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

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

Laser Detonation Enhanced Supersonic Metallic Coatings

Laurent Michaux

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

This project is investigating a novel method for the treatment of metallic coatings using shockwaves generated using a high energy pulsed laser. The laser-material interaction will be studied to better understand the shockwave generation process, and the resultant effect this has on the bulk material.

Of particular interest is understanding how such an interaction could lead to:

- Improved material consolidation and strength
- A modification of stress state of the material

A metallic coating technology that would benefit from enhanced surface properties is Supersonic Laser Deposition (SLD). The SLD process deposits powdered coatings, in the solid state (non-melting), onto metallic and non-metallic substrates.

When compared to melt based processes SLD has the advantage of retaining the enhanced nano-structured properties of the coating material, such as low friction and hard wearing.

SLD accelerates tens of micron size powder particles up to speeds approaching 700 ms^{-1} through the use of supersonic gas streams. The particles impact on a substrate, which has been "softened" with a multi kilowatt laser, and plastically deform the lower layer to build up a dense coating.

On some materials the current process leaves gaps between individual particles, which can lead to problems such as cracking and delamination. The coating needs better consolidation and an increase in bond strength. This would increase the performance of the coatings in applications of high density coatings for hard facing or the repair of engineering components.

Laser-Material Interaction

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

Work has been done to identify and understand a shockwave technique capable of modifying material properties near the surface using laser pulse energies of the order of 10 joules. Such a technique would work like an optical hammer on the material. The shockwaves generated from the laser-material interaction are thought to be suitable for processing deposited SLD coatings and affect particles to a depth of over 1mm.

A laser system has been designed and built to test this laser induced shockwave process and work is ongoing to understand the laser material interaction and process parameters.

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 desktop-size machine tool. The research will be made by design and development of a mechatronic system leading to high-dynamic motional control of desktop-size machine tool as required for free-form manufacturing. The research products will be implemented in the desktop-size machine tool – μ4 made by Cranfield 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 design and high-dynamic motional control performance into one solution based on experimental and simulation work.

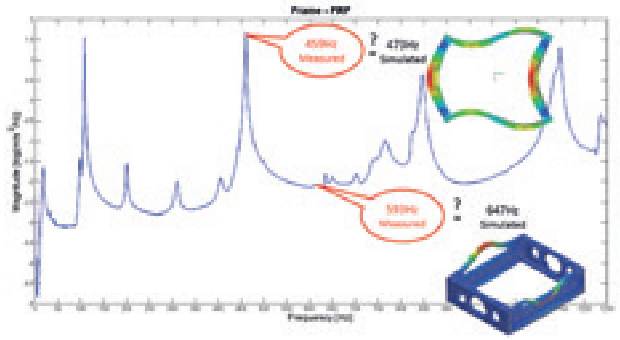
The μ4 motion axes modules can be used as a test rig to identify and specify the current design and to validate the improvements during this research. The system identification methodology is a bottom-up process in which the lowest level components are tested and simulated first, then used to facilitate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

The modal properties of the motion axes module were simulated using Finite Element Method (FEM), measured and analysed using modal measurement equipment specified and procured for this research. This work has been published as an oral presentation in the Proceedings of the 12th International Conference on Manufacturing Research (ICMR 2014) and as a poster presentation at the 3rd Annual EPSRC Manufacturing the Future Conference.

As a product of the modal analysis, a new mechanical design of the motion modules has been made. The design will be improved using FEM based on the knowledge of the correlation between the FEM and the modal measurements.

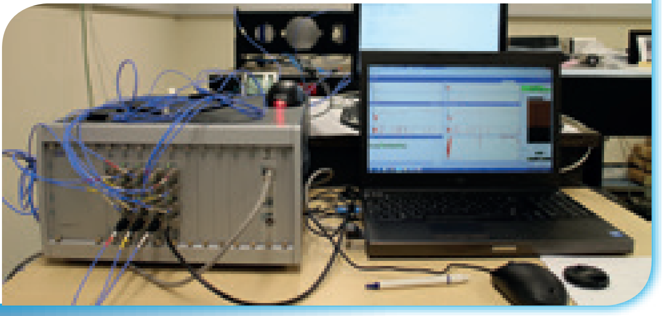
Based on the simulated and measured modal properties the structural vibrations of the motion module frame due to position commands were measured and analysed using the modal measurement equipment. The motion module control system was connected to the modal measurement system and used as an input/output for the vibrations measurement. These results will be used to investigate which control technique should be used in order to achieve high-dynamic motional control. The control technique will be based on a neural network of low-cost accelerometers. Several solutions are considered – adaptive filters, gain scheduling or a feed forward control.

The current phase of the project is focused on improving the mechanical design and measuring and analysing of the structural vibrations of the motion module.



Comparison between measured and simulated modal properties

Modal analysis and control systems



Precision Engineering of Advanced Air Bearing Systems

Murchaidh McRoberts

The project looks to develop high precision air bearings for application on two research platforms within the Centre, an important aspect of the work is to produce affordable air bearing systems using nickel plated aluminium alloy base materials. The initial work will centre on the μ4 6-axis milling machine, where current bearing technology has been unable to meet the demanding requirements, with bearing systems consistently failing. From an understanding of this work a bearing system will be designed and produced to support and actively position control large rollers on the R2R platform.

Ferroelectric Liquid Crystal Displays and Binary Dithering Schemes

George Meakin

This PhD project continues from George's MRes individual research project which assessed the viability of Ferroelectric Liquid Crystal (FLC) displays. FLCs were widely researched in the '80s and '90s, but were never successfully commercialised due to low refresh rates and manufacturing difficulties. FLCs are only currently used in reflective SLM microdisplays, where they are outperformed by DMD systems.

FLC displays have a binary transmission response and fast switching time similar to established DLP projectors, which should allow them to be used in high performance transmissive displays for mobile, PC and Head Mounted Displays.

As part of the research, the theory behind binary dithering was investigated. This is how different colours and grey values are produced by pixels with binary transmission. The pixels must be switched on and off at the correct times and synchronised to primary colour backlights, in order to control the amount of light that can pass for each video image. An investigation from first principles revealed a novel binary dithering algorithm that gives refresh rates an order of magnitude higher than the traditional method. George will be working with Cambridge Enterprise to pursue commercialisation of this technology.

With a switching speed equal to those demonstrated for previous FLC research, this scheme would allow for refresh rates of above 500Hz, if the pixel rows can be programmed in 100nm or less. This refresh rate is much higher than any current transmissive display, which could provide significant advantages for Virtual Reality, where a high refresh rate reduces visual errors and nausea while improving immersion. Virtual Reality is fast growing market that will require next-generation displays in the next decade.

An FLC display would also have a maximum pixel density three times higher than other LCDs, because coloured sub-pixels are not required due to sequential colour, where each primary colour is displayed in sequence using a single pixel. Sequential colour also increases lighting efficiency to 300%, increasing battery life by 50% for video playback on typical mobile devices. Altogether this potentially allows a FLC display to outperform other LCDs in all areas.

The electronics and manufacturing requirements for a commercial FLC display were investigated, with the conclusion that the technology already exists to support a commercial display. However, further work on the detailed design of an optimal FLC material, electronic driving scheme and digital system design is required before commercialisation can be considered. This design work is the focus of this PhD research project.

Active Magnetic Bearing for Ultra Precision Plastic Electronics Production System

Mathias Tantau

Mathias Tantau, a Masters student from Germany has designed an active magnetic bearing for the printing roll of the reel to reel platform (see Figure 1). The active motion control of magnetic bearings allows independent adjustment of bearing stiffness and damping, as well as compensation of machining inaccuracies in the whole spindle. The quick assembly of a magnetic bearing could expedite the change of printing rollers between different layers of the produced flexible electronics circuit.

The magnetic bearing shown introduces a novel technique to measure the radial position of the shaft; surface encoders count concentric fringes on the face of a reference disc and subsequent electronics generate incremental position information. This self-made scale utilises the high resolution and secure noise rejection of incremental systems compared with ordinary, absolute gap sensors, which are mostly used in active magnetic bearings.

If the proposed magnetic bearing is really reconcilable with ultra precision and if the performance of a magnetic bearing can compete with a hydrostatic bearing of the same size, this has to be further investigated in the research project. To achieve this objective a simpler prototype shall be designed, machined and assembled, programmed and tested in the remaining months of research project.

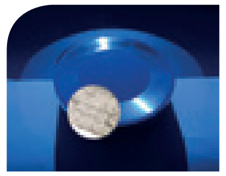


Fig 2: Mirror finished aluminium disc with 10μm grooves cut by a diamond turning machine as encoder scale

Fig 3: Radial bearing

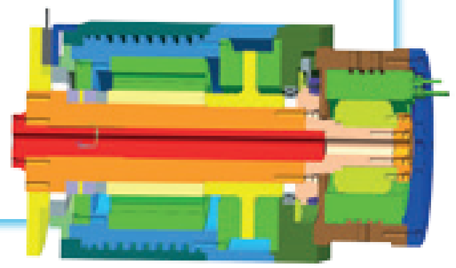


Fig 1: Active magnetic bearing NX design for the reel to reel platform

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

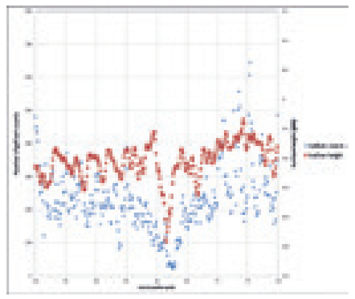
Matt Bannister | **Sponsor:** Carl Zeiss

The effects of laser fluence on the removal of ion beam implanted gallium have been studied on silicon and glassy carbon. Substrates were implanted with gallium ions at a dose of 4.17 x 10^{21} ions/cm^2 and subsequently processed using a 1030 nm wavelength, 280 fs pulse duration ytterbium fibre laser over a wide range of pulse energies. Changes in gallium ion concentration were measured using energy dispersive x-ray spectroscopy (EDX). EDX analysis showed that, for pulses with fluences below the damage threshold of the material, there was no change in overall gallium concentration, meaning that no removal from the surface occurred. However for pulses just above the damage threshold, the removal of a thin layer of substrate material resulted in a reduction in gallium ion concentration, as can be seen below. Further investigations into femtosecond laser polishing as a technique for removing ion beam implanted gallium are ongoing.

An alternative solution to femtosecond laser processing is being investigated – ultra-violet (UV) picosecond laser processing. Extensive simulations of the implantation of gallium ions into silicon and carbon have shown that the implantation depth of the ions is limited to around 100 nm or less in both substrates when implanted with a 30 keV gallium ion beam. However the absorption length of IR radiation at a wavelength of 1 μm is of the order of tens of microns in silicon. By changing the wavelength to the UV region of the spectrum the absorption length becomes comparable to the implantation depth of the ions, and has the potential to be used for annealing out the implanted gallium. A 355 nm Talisker laser, with a pulse duration of 10 ps, is to be used to process implanted substrates to try and remove gallium. The laser system is currently being installed and shall be used for annealing and polishing of the implanted substrates.

In comparison to optical techniques, conventional furnace thermal annealing has been found capable of achieving out-diffusion of implanted gallium ions. Silicon implanted with gallium at a dose of 4.17 x 10^{21} ions/cm^2 was annealed at 800 & 900°C for 15 minutes in a flowing nitrogen atmosphere. EDX analysis of annealed and un-annealed substrates was again carried out to determine any change in gallium concentration. It was found that annealing caused a reduction in gallium ion concentration from 14.9% in the un-annealed samples to 8.0% in the sample annealed at 800°C, and further to 3.9% in the sample annealed at 900°C. Further investigations into the effects of annealing temperature and duration are ongoing.

Currently analysis of annealed substrates is carried out by EDX. However the interaction volume of the electrons to generate x-rays in EDX is greater than the implantation range of the ions – therefore any changes in ion distribution within this volume cannot be detected. A mass spectrometer has been obtained from the EPSRC loan pool for use in February to April 2015 and shall be used in conjunction with the Satsuma femtosecond laser to carry out some laser induced – inductively coupled plasma – mass spectroscopy (LA-ICP-MS) studies. Single pulses from the Satsuma will be used to ablate very small amounts of material from the sample surface. The ablated material passes into the ICP-MS system which is used to determine the composition of the analyte. By drilling further and further into the material and analysing the ejected material after each pulse, a depth profile of the gallium distribution will be developed. This shall be used to determine the sub-surface profile of gallium for samples annealed with the femtosecond and picoseconds laser systems.



EDX profile (blue) and interferometer profile (red) showing a decrease in gallium ion concentration corresponding with machining of the surface for silicon implanted with gallium ions at a dose of 4.17 x 10^{21} ions/cm^2 and processed using Satsuma fibre laser at a fluence of 13.54 J/cm^2

Design and Development of Solid State Additive Manufacturing Techniques

Sam Brown

Solid state deposition has recently been shown to be capable of manufacturing components from a range of materials, from relatively soft to wear resistant. The purpose of this research project is to investigate new materials and new manufacturing routes, with the initial aim to create high performing bearing surfaces for motor applications. This will require investigation and optimisation of materials production, handling, deposition and testing. The process developed should be applicable to other practical uses of the technology, such as direct part creation and component remanufacture.

Nanomaterial Based Field Emission X-Ray Sources

Clare Collins | **Sponsor:** Cambridge X-Ray Systems and Cheyney Design & Development

This PhD research project started in October 2014 and continues from the work that was undertaken as part of Clare's MRes individual project between May and August 2014. The project developed the modelling of a CNT array by designing and manufacturing arrays and performing experiments on them to assess the behaviour of the electrostatic field with differing geometries. Fowler-Nordheim sweeps at individual points across manufactured chips and build up a 3D picture that will map the electrostatic field.

Comparisons across a diverse range of materials from other authors have been made, all of which have been proposed for the use in field emission. These studies will be continued throughout the PhD, as well as working experimentally on a range of suitable materials in a specially designed Scanning Anode Field Emission Measurement machine. These studies will advance field emission by covering a range of materials and ultimately aim to determine the underlying physical forces that govern emission performance of materials, which are currently not fully understood.

High Speed, High Power, Variable Beam Diameter Laser Additive Manufacturing of Metal Powders for Medical Applications

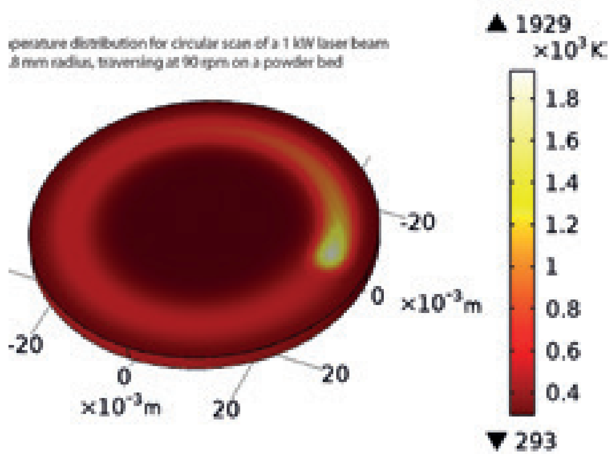
Jonathon Parkins | **Sponsor:** Stryker, The Worshipful Company of Engineers

A new technology approach is proposed for rapid fabrication of biomedical implants from biocompatible metals using powder bed-based laser additive manufacturing. Existing technologies cannot significantly increase the throughput of flexible additive manufacture. Therefore, a dedicated fabrication route is investigated for the acetabular cup – part of a hip replacement.

This research will develop a method of rapidly consolidating the bulk material region of an acetabular cup to reduce total process time. It will also provide a system comprising the new bulk material fabrication route alongside existing fine featuring technology to rapidly produce the components. The main contribution to literature will be an investigation of the interactions between a laser beam and metal powder in previously unexplored parameter ranges.

A test platform based on a new scan unit has been designed and is being built. It will be used to refine the process parameter envelope for high power, high speed and large diameter laser beam conditions. This platform will be the basis of a part fabrication machine in combination with existing galvanometer scanners and powder handling capabilities. This system will be created when the laser-material interactions have been characterised.

A thermal model has been developed to increase understanding of the temporal ion of the process for a range of parameter combinations. The temperature distribution within the powder bed is calculated by a finite element method. The model provides an indicator of melt pool geometry and size based on temperature. The predicted melt pool data can be examined relative to known literature which describes maximum aspect ratios of molten regions during welding processes, limited by fluid dynamics. The thermal gradients observed also indicate the residual stresses that will develop in the part. Experimental verification of the model predictions of geometry will be performed upon completion of the new scanner.



A thermal model is used to predict the available process parameters to achieve melting without ablation. The balance between power, scan speed and beam diameter can also be used to control thermal gradients and hence residual stresses.

Production of Carbon Nanotube Based Cold Field Emission Cathodes

Francisco Orozco | **Sponsor:** Air Force Office of Scientific Research, Air Force Material Command, USAF

This project aims to develop a customized device capable of producing repeatable, reliable emission cathodes with an emission of more than 10 mA that can be applied as sources of high power microwaves in the Air Force Research Laboratory (AFRL), Directed Energy Directorate. Initial work has shown the difficulties in producing repeatable cathodes due to variations in material properties and geometry.

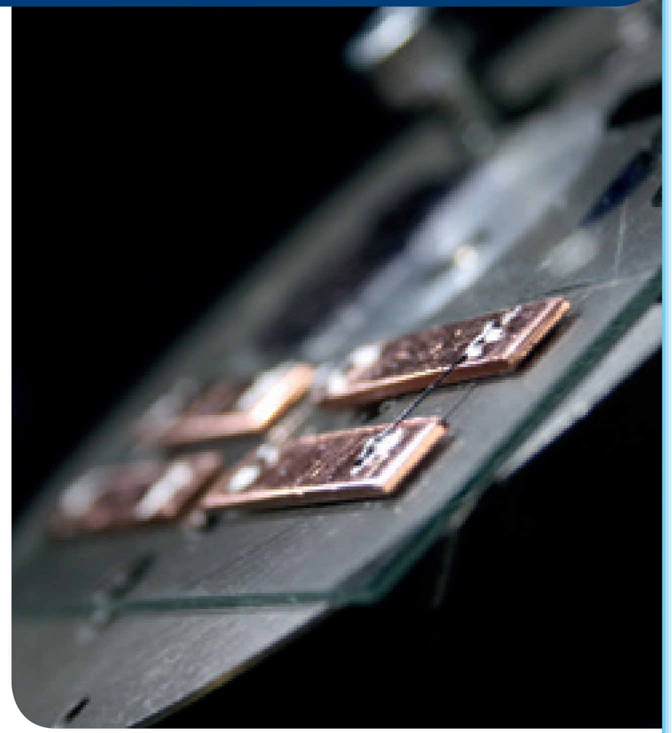
The project focuses on:

1. Production of arrays for testing
2. Solving the material handling of Carbon Nanotube (CNT) fibre by having a controllable macro stiffness of the fibre
3. Design of process for cathode fabrication
4. Scalable production route for fibre arrays

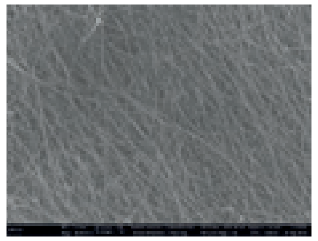
Currently the first two points are being concentrated on, being essential for the remainder of the work.

Production of arrays: Fibres are first characterized (microscopy, SEM and Raman), then mounted onto copper plates which serve as a fixture for testing (bonded with silver ink) before being laser trimmed. Mounting and cutting of the fibre onto copper plates has proved challenging especially when trying to align two or more fibres to create arrays. A microscope (500x) mounted in parallel to the laser path is used to visualise the sample inside the same chamber where it is being processed. Initial samples have shown a difference of height of ≈ 13 µm between the cut fibres in arrays due to issues with measurement datums. Experimental work predicts that the tops of the CNTs need to be within ±5 µm for uniform emission. Current tests are looking at grinding the copper mounting plates on one edge to give an accurate surface for aligning the laser cutting process.

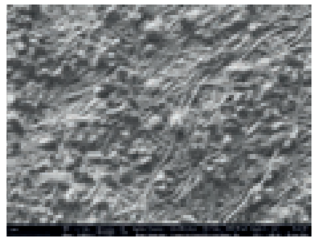
Material handling/fibre rigidity: It is important once mounted that the fibres remain in place for repeatable emission. This problem has been investigated by considering: a) deposition of materials onto the CNTs, b) placing CNTs on substrates and c) densifying the fibre. The first material that has been deposited is diamond like carbon (DLC). DLC has been found in literature to be used for FE as coatings for metals improving the emission data. A small sample has been prepared as proof of concept to confirm the CNTs survive the cutting process and emit well. Emission trials are also looking at the effect of mounting CNTs directly on the edge of substrates, with no emitter protrusion (results awaited). Densification routes are looking promising.



Single fibre laser processing



CNT film



DLC coated CNT film

Holography as a Consumer Display Solution

Matt Pryn

This research project involves developing a prototype system capable of displaying full colour, three dimensional video to multiple users simultaneously. Research areas will include: optimising current display hardware to enable high quality images with wide viewing areas, efficiently generating depth perception by hardware and CGH algorithms, and display drive electronics. Expected challenges include data management, sufficient image quality to displace commercially available displays, system size, longevity and reliability, and multi-person viewing.

Ultra Precision Hybrid Laser-FIB Platform

Chris Wright

The proposed project will investigate the integration of processing using the laser and FIB systems to increase the throughput of ultra-precision manufacturing. The main objective will be to provide a system capable of producing large scale 3D profiles; the bulk processing will make use of the ultrafast laser and fine detail featured using the FIB. The process train developed will give the advantage of high throughput whilst maintaining accuracy when compared to current FIB technology. There are a number of challenges to be addressed which include:

- Development of a carriage to allow transfer of samples between the two platforms
- Establish correlative microscopy between the two systems
- Extraction of numeric 2D and 3D metrological data from both systems
- Development of a process train or feedback control system capable of taking the measured data and correcting for the desired form

The first year of the project will involve establishing the basic capability of the process, targeting optimised production of 2D structures. Subsequent years will optimise and extend capability to 3D.

Holographic Enhancement of Fibre Optic Sensors

Jaliya Senanayake | **Sponsor:** Michell Instruments

This research focuses on investigating the performance of evanescent field fibre optic sensors with the modal decomposition of light passing through the fibre. Modal control is achieved using a Holographic Launch method. With the replay field focused onto the fibre facet, the hologram can be controlled such that the overlap integral between the replay field and the targeted mode field is a maximum.

Previous work showed that this launch scheme was made possible by superposing a phase pattern on the SLM, which corrects for aberrations and distortions of the optics.15 Zernike polynomials were incorporated in the search algorithm which determines this correction pattern. Recent work shows that, rather than using normalised Zernike polynomial patterns, when scaled to have an even impact on the replay field (by visual inspection), higher order polynomial terms can be effectively added to the optimisation, allowing for better correction patterns. The search algorithms were reviewed and optimised for using 35 Zernike terms, to yield good corrections and short run times.

When generating holograms for exciting a specific mode, there exists an optimum illumination beam width on the SLM, for highest efficiency in the replay field. This becomes significant in heavily multimode fibres where the highest order modes require an illumination beam of smaller diameter. To control the illumination beam size on the SLM the 3 lens arrangement shown in Figure 1 is proposed. The lens F_i (of long focal length), converges the beam slightly, hence by shifting its position toward or away from the SLM, alters the illumination beam size on the SLM within limits. The replay field remains in focus, so long as the optical path length between F and the 35mm lens is equal to the focal length of lens F. While this scheme does allow for efficient excitation of the highest order modes, requiring two moving parts, re-aligning the fibre and positioning the lenses accurately is extremely difficult, and perhaps not a feasible option.

Humidity sensing experiments performed with the side polished evanescent field sensors, showed that the transmitted power varies linearly with the dew point temperature of the sample. Further tests show that for the same launch condition, with measurements performed at different launched power levels, the lines of best fit extrapolated all converge at a point (see Figure 2), and the coordinates of this point vary depending on the launch condition. The physical origin of this convergence point and how it changes with the launch conditions are not yet fully understood. However this result strengthens the notion that the relation between dew point temperature and power is linear, and also provides an additional constraint for normalising power levels when comparing sensitivities where different launch conditions couple different power levels into the fibre. Furthermore, this convergence point is related to the measurement sensitivity, and may be used to simplify analysis of results.

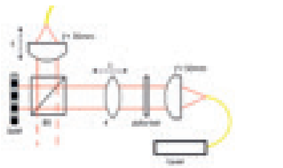


Fig 1: Three lens mode launch configuration to control the illumination beam size on the SLM

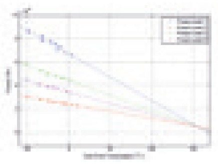


Fig 2: Dew Point Temperature vs. Power measurement at 4 different power levels, with the lines of best fit extrapolated

Diamond Machinable Coatings for Fluid Film Systems

Peter Xia

This project aims to recommend process route(s) for producing optical quality, wear resistant, diamond turnable coatings suitable for use on components of reel to reel (R2R) production equipment. Thus this work plans to enhance the coating quality currently available and reduce the defect rate for components such as the rollers and bearing housings. Defining and benchmarking coating quality is the current focus to provide suitable and relevant assessment of coatings carried out in house and externally using suitable descriptors for specifications of quality.

Current progress has been made in the following areas:

1. Identifying potential coatings for depositing on the bearings and rollers

A literature review has shown that there are limited amounts of materials that can be diamond machined. One "mature" coating method that is suitable for improving the wear resistance of the substrate is an electroless nickel coating with a high phosphorous content (>10%). An amorphous structure of nickel allows the diamond machining tool to wear less. The to-be-coated substrate also contributes to the final surface finish.

2. Assessing coating quality

Benchmarking surface finish as an optical quality coating surface

The pre-plating history of a component's surface has an influence on the final coating quality. Benchmarking is being carried out using unplated steel and also diamond turned copper, aluminium and specimens and comparing them with the as-plated version (before and after diamond turning). In order to define the factors that make the coating optically "finished", the surface morphology is the key. The smoothness of the coating surface can be affected by both pre-plating treatments such as pre-plating machining processes, pre-plating chemical surface treatments and post-plating damage which arises through the plating process itself. Pre-plating treatments such as alkaline degreasing, mechanical polishing, and acid pickling can be applied to remove the surface oxide or scale and provide necessary activation to the surface for plating. Additional treatments prior to plating, for instance a zinc deposit is required to act as a transition layer between an aluminium substrate and the electroless nickel coating. This prevents the plating bath from etching the aluminium to be plated, reduces the growth of an oxidizing layer and hence provides good adhesion. Post-plating damage can also occur during relocating of the plated articles.

Fig 1: Aluminium substrate prior to plating[1]

Defining descriptors that describe the coating

Close inspection and characterisation of in-house plated specimens and commercially plated specimens is being used to detect and identify the defects. It is important to know what constitutes a "defect" in terms of the functionality of the component and whether this will have an effect on subsequent diamond-machining that the component might undergo.

Coating morphology

The as-plated coating surface shows the coating surface is smooth with micro features as small as 1 μm as in Figure 2. The majority of undesirable features, for example a micro defect from an inclusion caused by external particulate adhering to the surface during plating, may occur at any stage of the plating process. Adherent particulate matter can cause either a void or result in a raised "bump" or "bulge" on the surface of the coating and in addition, cracking due to coating's internal stress can also occur.

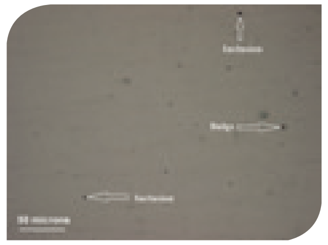


Fig 2: Nickel plating on steel substrate showing defects

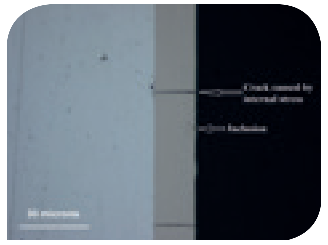


Fig 3: Coating cross section showing stress induced crack

Coating thickness and composition

To measure the coating thickness, the sample has been sectioned and measured under an optical microscope. The plating coating rate obtained in house is 18 μm/h. Figure 3 shows the coating can be uniformly deposited and Figure 4 EDS analysis indicates that the coating has 9.92wt% for the phosphorous content.

Further work is being undertaken to plate aluminium since early trials were undertaken on steel, and to understand the influence of the surface finish and plating parameters on the final coating quality.

Fig 4: EDS analysis of the coating with Ni 9.9wt%P

Control System for Ultra Precision Processing

Karen Yu | **Sponsor:** IPG Photonics

High precision manufacturing of nano- and micro-sized objects has become increasingly prominent given current technological trends. However, while traditional macro-manufacturing systems rely on automatic feedback loops to detect errors and act immediately, this is a more difficult task when scaled down to the single micron or less. The goal of this project is to provide feedback and control to laser based ultra-precision (feature at or below 10 µm) processing platforms. Several different metrology techniques were chosen to modularize the overall system and cover specific industrial needs.

In the period spanning May to October 2014, the swept source optical coherence tomography (SS-OCT) inspection system has been developed, constructed, and undergone troubleshooting and characterization. The primary purpose of this system is point inspection and in-situ point monitoring/feedback. Table 1 shows the designed performance specifications of the OCT system. It should be noted that these specifications were chosen as an initial proof-of-concept and can be changed and tailored to specific industrial applications.

Figure 1 shows the completed system. Much of the hardware seen in Figure 1 is fibre based, allowing for the overall system to be reduced in size when integrating with processing platforms. The software for the OCT system has also been developed with Figure 2 showing the live display of the OCT image and identified object depth. Figure 3 is a plot of the filtered data OCT taken at varying depths, which show that the system will have a coherence length that surpasses the initial target.

The next immediate step is to continue troubleshooting both the hardware and software of the system as it does not (at present) meet the expected axial resolution. This is most likely related to the signal sampling and will be solved concurrently with developing an integration strategy with a laser processing platform. The system will be miniaturized with the fibre port providing a common connection interface with existing laser processing systems. At the same time, additional algorithms will be developed to take advantage of the A-line rate to provide closed loop feedback.

Axial Resolution	7.5 µm
Depth of Field (Coherence Length)	> 5 mm
A-line rate	100 kHz

Table 1: SS-OCT design specifications

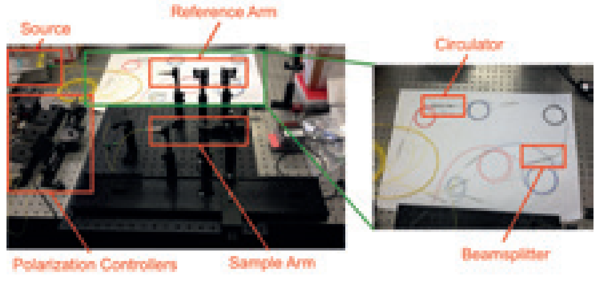


Fig 1: SS-OCT hardware setup

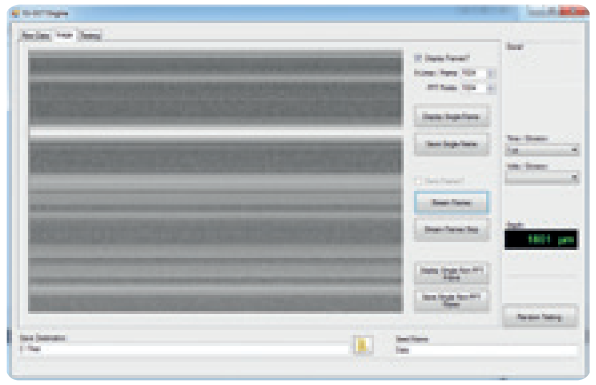


Fig 2: SS-OCT software displaying live data and showing the identified object depth

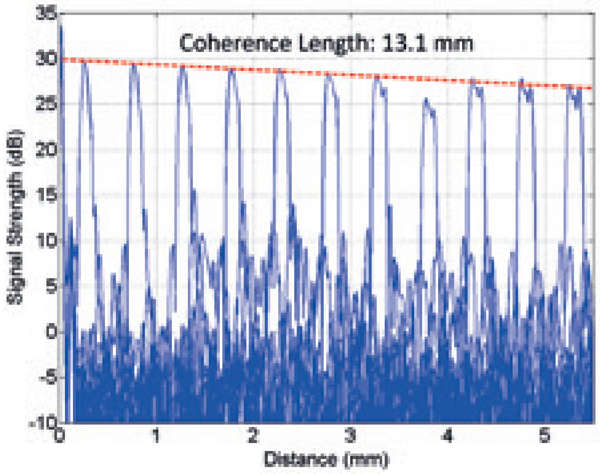


Fig 3: Filtered SS-OCT depth data showing the slow drop-off of the signal and calculated coherence length of 13.1 mm

Ultra Precision Light Sensor

Chris Williamson

It was previously reported that vertically aligned carbon nanotubes (CNTs) had been grown directly onto a silicon wafer. In order to have a degree of control of field emission, it was determined that a conductive underlayer to the catalyst was required which would enable a circuit to be patterned prior to CNT growth. Figure 1 demonstrates growth using titanium which is whispy and it was not possible to improve on this result. The reason for this is that the Nickel catalyst layer diffuses into the Ti underlayer and the resultant catalyst sites are very small. Similar problems were found with all metals. It was found that an oxide based underlayer yields good growth (Figure 2) and when the layer is thinner than 4nm electrons can tunnel through to a metal layer below. Unfortunately around the same threshold, the oxide layer is too thin to improve growth and diffusion of the catalyst into the metal underlayer is dominant. The solution to the problem was to use indium tin oxide (ITO) as an underlayer which is conductive and also an oxide. A 10nm ITO layer with 6nm Ni catalyst layer yielded uniform vertically aligned CNTs on a conductive material which is an ideal platform to build a field emission circuit onto.

Further tests considered adhesion strength of the CNTs by inserting the samples into an ultrasonic bath. Adhesion is non-uniform across the sample but certain areas remained adhered for approximately five minutes. A more thorough cleaning of the substrate is likely to provide improved adhesion.

Patterning the catalyst sites into approximately 100nm dots allows for positioning of individual CNTs and this was previously achieved using a focused ion beam which allowed for precise and rapid patterning of small areas. There were numerous problems involved with this approach which included a difficulty in scaling up the process and costs involved. Being a vacuum based process, it would be very challenging and impractical to incorporate a FIB onto a roll to roll platform which is the envisaged aim of this project. The ion beam can also only process a small area before having to move the stage and to process a sample around 1 cm^2 would be very time consuming. Additionally the ion beam and electron beam charge up the sacrificial insulating polymer mask making precise milling difficult.

The patterning process has been moved towards a femtosecond laser which cannot provide as fine a resolution as the FIB, but is much easier to implement without a vacuum and the resolution is sufficient for the needs of this project. Initial samples were observed using the AFM and holes around 1µm were observed. An updated sample has been made and is awaiting processing.

Problems with the screen printer on the roll to roll platform have been considered. The blade setup has been modified and a new screen has been ordered. Steps have been taken to resolve issues with cleaning the screen after use and a pumping system has been designed and ordered to resolve problems related to feeding adhesive into the screen effectively.

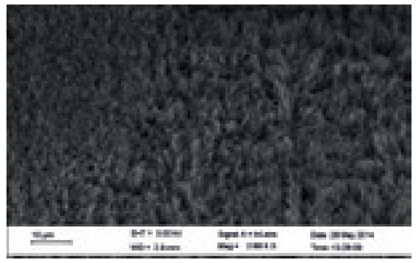


Fig 1: Ti underlayer

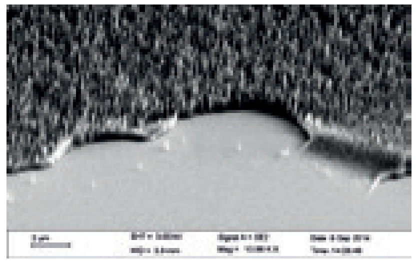


Fig 2: Al_2O_3 underlayer

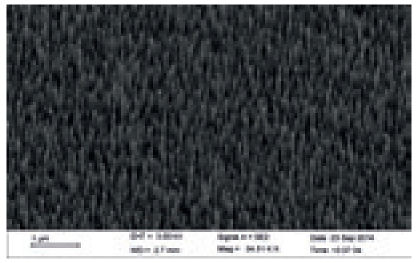


Fig 3: ITO underlayer

High Speed Mask-Less Laser Controlled Precision Additive Manufacture

Jason Ten | **Sponsor:** Agency for Science, Technology and Research Singapore

This PhD project has been initiated to develop a laser-based precision additive manufacturing route for the Laser-FIB platform at the University of Cambridge. Tentatively, the process will be based on a laser assisted chemical vapour deposition system. The desired capability of the system is to deposit a range of materials at locations controlled by a laser with minimal contamination. These deposited materials may connect other multiple materials, add functionality or build 3D geometry at the micrometre precision level. It is envisioned that such a capability is vital for deposition on fragile materials such as graphene and carbon nanotubes for the manufacture of next generation devices.

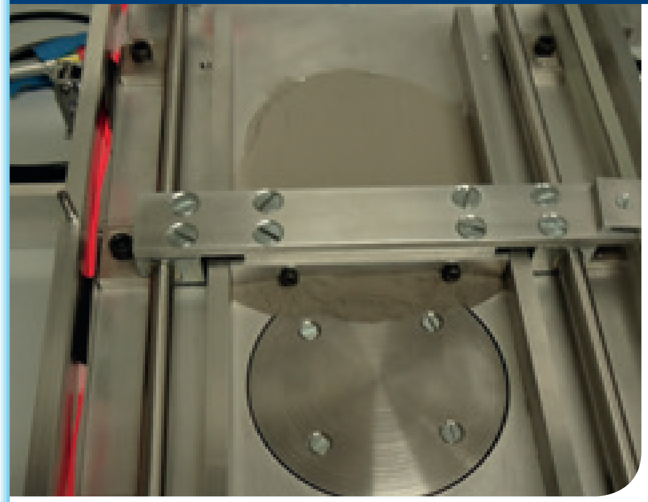
Advanced Technologies for Ultra Precise Light Weight Space Optics

James Norman

The ever increasing need for larger space optics has led to requirements for space mirrors to have lower areal mass density whilst maintaining the trend of increasing form accuracy at lower cost. The properties of silicon carbide (SiC), such as its high stiffness and high thermal diffusivity, make it an excellent candidate as the substrate material for such space mirrors. This PhD research will endeavour to significantly reduce the cost of producing SiC space optics through designing for manufacture whilst improving upon the form accuracy of current optic designs with lower areal densities.

Multiple Beam Powder Bed Fusion Additive Manufacturing

Andy Payne



The wiper mechanism in the process of spreading the first layer of powder over the build platform

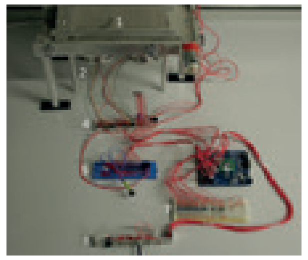
The aim of this project is to improve thermal stress management within the context of powder bed fusion additive manufacturing. Poor stress management can lead to processing defects such as buckling, warpage, de-lamination and in some cases can terminate the build if the powder re-layering mechanism fouls upon a protrusion of the part. Differential cooling contributes to these detrimental distortions and exists due to the intense localised heating followed by rapid cooling of the top surface and the relatively slow convection through the powder bed at the bottom of the part. The use of multiple beams within the layer fusion phase will produce a wider distribution of thermal energy within the layer thus delocalising thermal stress and allow for higher build rates which reduce the thermal gradient in Z thus further reducing stress. This research seeks an appropriate scanning strategy to maximise the thermal stress relief conferred by the use of multiple energy beams.

To enable this work an atmospherically controlled processing chamber with automated re-layering mechanism has been built. The design of the chamber comprises two cylinders: one cylinder is used for the powder supply and one as the build volume. Stepper motors with a 25 µm resolution are used for the piston movement and give a build envelope of 100 mm diameter by 70 mm deep. The re-layering mechanism is belt driven by a speed controlled DC motor and carries an interchangeable wiper blade. Atmospheric control is achieved in a 50 mm thick layer above the machine bed and can be nitrogen or argon filled depending upon process requirements. The processing chamber has an overall size of 450 x 250 x 300 mm and has been fabricated and built in house.

Interface electronics have been developed to sit in between and coordinate the various sub-components of the system: the processing chamber, beam movement control and beam delivery timing. Currently the system is controlled by a PC but the interface electronics are microcontroller based which allows for flexible expansion of duty. In operation the microcontroller accepts single bit signals from the PC and translates these single bits into the chains of instructions that each subcomponent requires.

The system has not long been operational and trials to establish the relationship between exposure times and melt volume have been carried out using stainless steel 316L in a nitrogen atmosphere. These early trials have proved successful however upgrades to the control electronics are being carried out to improve timing and power control before further trials are carried out.

Single layer test part built from stainless steel 316L



[1] Processing chamber, with lid off
[2] Stepper motors underneath cylinders
[3] DC motor for wiper movement
[4] Power handling circuitry
[5] Energy delivery timing circuitry
[6] Microcontroller
[7] Beam movement control circuitry
[8] Manual controls

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

Nan Yu

In the past five months, the CFD model was improved with heat exchange and turbulent flow. This simple model has indicated some sensible results when compared to actual process data of removal footprints. Correlation data gives confidence for more detailed modelling work. Then, some initial design rules and nozzle parameter sensitivity analysis has been obtained. This information can be used to create a number of new nozzle designs for future experiments.

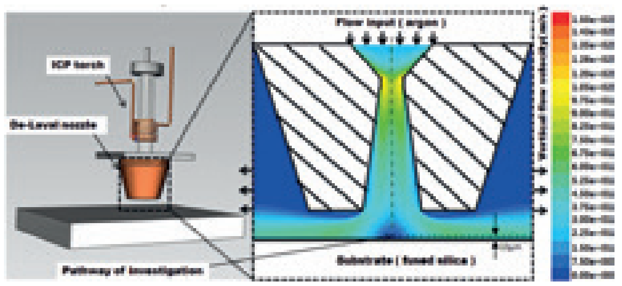


Fig 1: Overview of the CFD investigation. 3D drawing of the plasma figuring torch (left); 2D CFD simulation illustration of flow velocity in the nozzle (right)

1. Numerical simulation of plasma nozzle designs

Figure 1 introduces results from the initial computational fluid dynamics (CFD) modelling of the plasma torch nozzle designs, based in the software package FLUENT. The fluid is simplified to be high temperature argon gas, and is also assumed axisymmetric, uniform, steady and turbulent.

As shown in Figure 2 the "Pathway of Investigation" is characterised by regions experiencing either downwards and upwards flow directions. The negative regions are considered to be those which will experience the presence of the radical compounds. From a processing view point, the plasma etching is considered to take place only in the region exposed to free radicals.

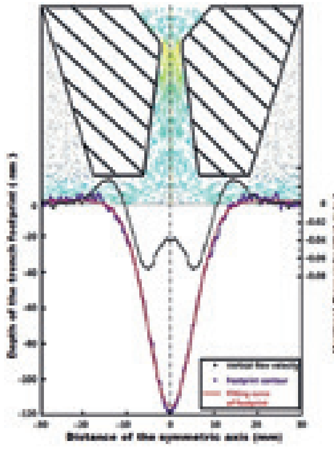


Fig 2: Curves of the etched area and gas velocity

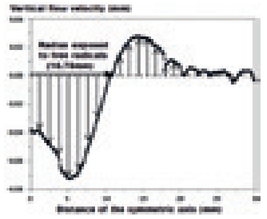


Fig 3: Vertical flow velocity plots along the pathway of investigation

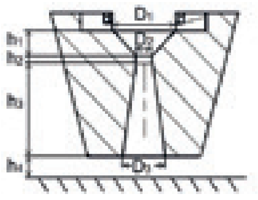


Fig 4: Parameters of nozzle

Figure 3 combines images from the gas flow simulation model and footprint experiment data (carried out in 2010, by Castelli). This figure highlights correlation between the material removal footprint and the regions exposed to free radicals.

2. Nozzle design evaluation using CFD model

Three of the nozzle's key design parameters have been changed to investigate their effect on gas flow: the diameter of the throat D2, the diameter of divergent end D3, and the depth of the divergent path h3 (Figure 4).

There are 3 general design rules of the De-Laval nozzle from the results in Figure 5:

- Radius exposed to free radicals decreases significantly as the throat (D2) shrinks
- Radius exposed to free radicals decreases when the divergent end (D3) shrinks
- Smaller energy beam footprints should be achieved with adjustment of D2 as it is more efficient than tuning D3

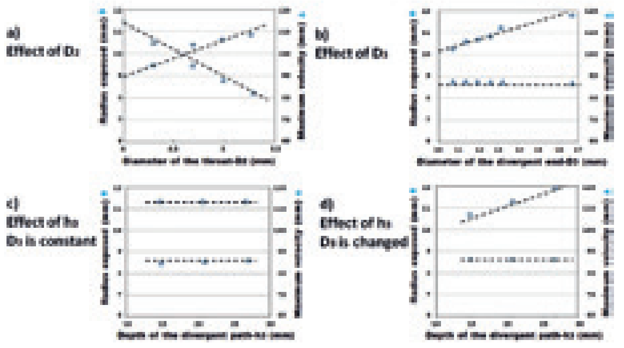


Fig 5: Design parameters versus the radius exposed to free radicals (♦); Design parameters versus the maximum velocity in the throat (▲)

Femtosecond Laser Direct Micro-Cutting Graphene for Device Applications

Tianqi Dong | **Sponsor:** National University Defense Technology

1. Research Background

Graphene is a single atomic carbon arranged in hexagon, firstly discovered in 2004. During the last decade, graphene has attracted enormous interest, emerging as an exciting new material with the potential to impact many areas of basic research and technology [1-3]. Graphene has potentially useful electronics properties, but it is difficult to pattern graphene in different geometry for devices. Although conventional lithography methods can provide precisely located nano/micro patterning and cutting on graphene, it involves a long sequence of process operations, which may also increase the risk of contamination. Femtosecond laser micromachining has the potential for offering free-form post-patterning of general graphene devices with limited thermal effects, high processing speed, complex shapes and high spatial resolution.

2. Research Progress

In this report, we demonstrate a uniform single layer micro-pattern of graphene on 285 nm thick SiO_2 on a Si substrate using a 1030 nm, 280 fs laser. The cutting process was conducted in air, the path determined through the motion of a high-precision translation stage. Approximately 1.6μm-wide graphene micro-channels were cut with uniform widths and clean edges. The ablation threshold of graphene was determined to be 0.066 J/cm^2~0.12 J/cm^2, at which the selective removal of graphene was achieved without damage to the silicon substrate. SEM images revealed high quality cuts, with little damage or re-deposition, as shown in Fig 1. The Raman maps showed no discernable laser induced damage in the graphene close to the ablated edge, as shown in Fig 2.

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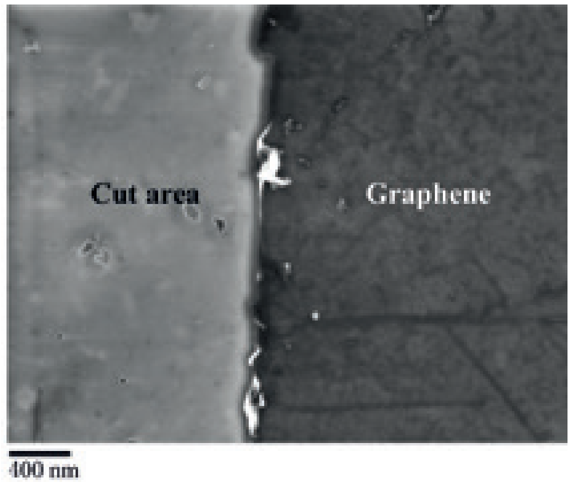


Fig 1: SEM image of cut and uncut area of graphene

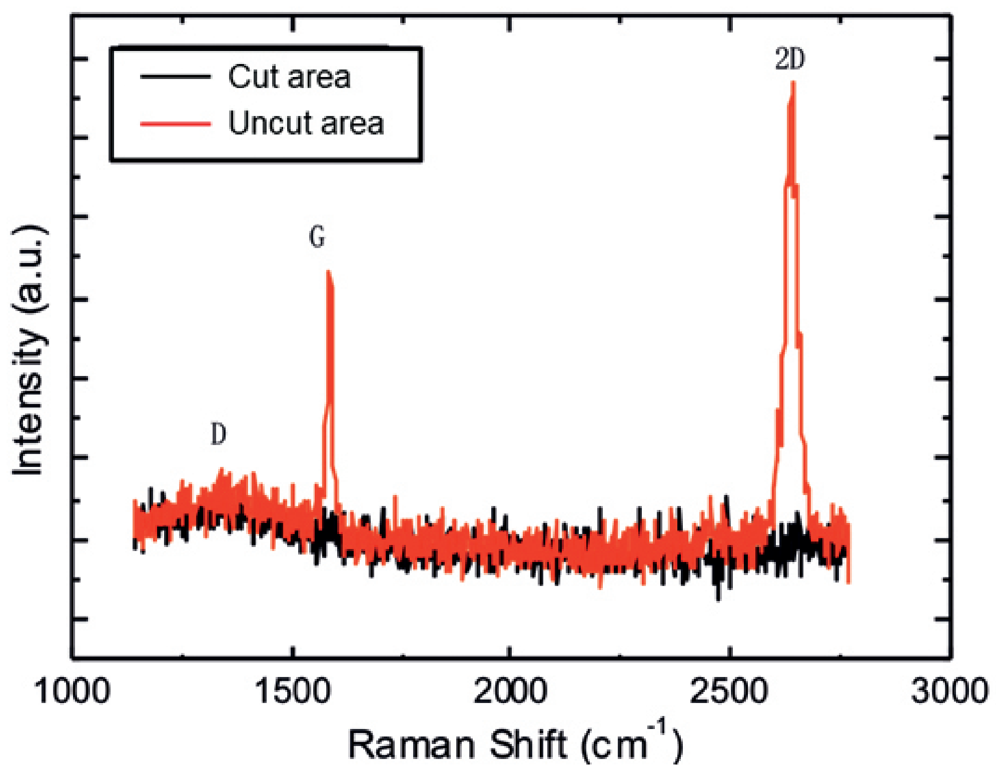


Fig 2: Raman spectra of the cut base and edge

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

Wenhe Feng | **Sponsor:** Amplitude Systèmes

1. Fabrication of basic microfluidics

The impact of etching temperature on FLICE was investigated. Figure 1 (a) shows a comparison of the tunnels' shape after etched under 40-80°C, on the same track processed with Hurricane laser that was tuned to 120fs, 5kHz, 40mW, 0.5mm/s. As the temperature increased, the etch rate became higher but the selectivity became lower, causing the tunnels to be longer, wider but more conical. Profiled buried structure was also written and etched and is shown in Figure 1 (b). On the other hand, surface channels with high aspect ratio were made by FLICE. Figure 2 (a) shows a sideview of laser-processed tracks buried in fused silica prior to etching. Satsuma laser was used for this application and tuned to 280fs, 100kHz, 100mW, 0.1mm/s. The sample was etched only under 120°C but not any lower temperatures to induce effective removal of modified volume and Figure 2 (b) shows these channels after 2.5 hours. The aspect ratio can be further improved by writing deeper tracks up to 20 mm only limited by the focusing optics.

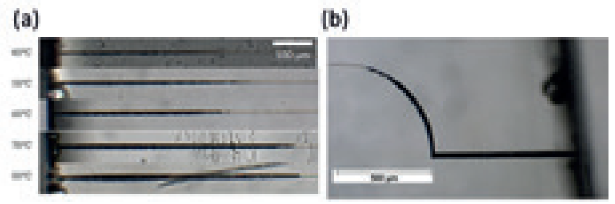


Fig 1: (a) Tunnels etched from the same track, under 5 different temperatures (b) A tunnel during etching that had a designed shape

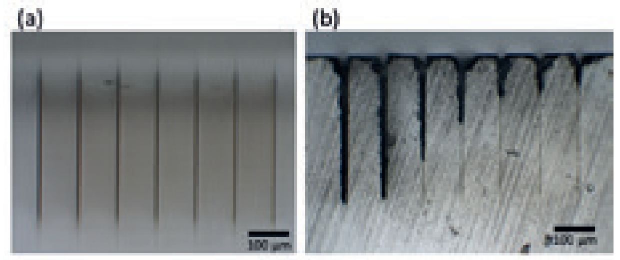


Fig 2: (a) Sideview of 7 tracks before etching, 150mW, 0.1mm/s, depth spacing= 2.5, 5.0, 7.5, 10, 15, 20 and 25 μm, horizontal spacing=100 μm (b) Same tracks after etching. The edge was then ground off to have a clearer sideview of the tracks' cross-sections

2. Mechanisms of selective etching

Raman spectroscopy was employed to analyse the laser modification to glass and its qualitative correlation to etch rate. The spectra of raw glass and modified glass processed with 130 fs, 5 kHz, 40 mW laser at a translation speed of 0.5 mm/s are shown in Figure 3. Among the peaks D1 and D2 represent the 4- and 3- membered rings in SiO_2 network, and the ω peaks are the intrinsic motion of the Si and O atoms. Stronger signal from 4- and 3- membered rings suggests a loss in oxygen in laser affected volume, turning the glass into SiO_x (x<2) which was Si-rich and hence react much faster with alkaline etchant. Next steps would be to numerically link the etch rate to peak magnitudes, and to map the area around the tracks to characterise the volumetric expansion of etched features from the laser affected zones.

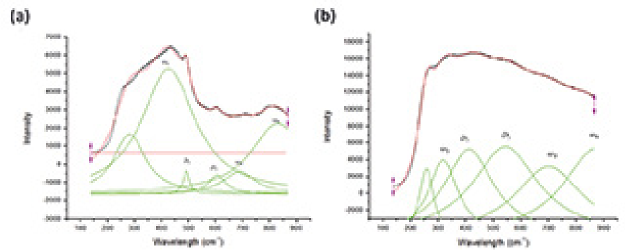


Fig 3: (a) Raman spectra of raw fused silica. Its decomposition is shown as green Lorentzian curves at a designated peak width of 100cm-1 (b) Raman spectra of laser-processed fused silica

3. Development of CAD/CAM process

A CAD/CAM process was developed in which the .stl model was sliced into layers in Gcode that was executable by Aerotech CNC stage. The production flow of a King chess piece is shown in Figure 4. To extract a 3D object from the bulk, a mould can also be made around the object. Potential applications are envisaged, such as optical fibre micromachining and blood-plasma separators.

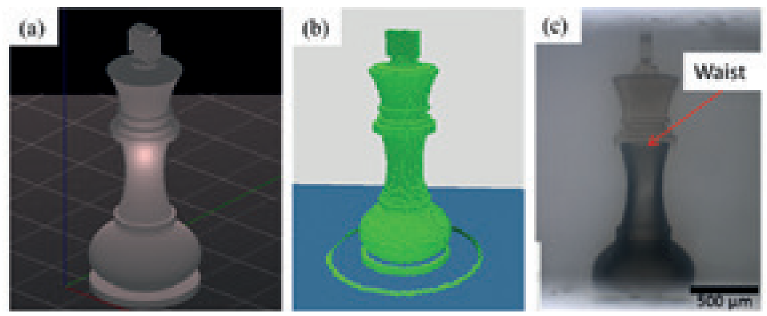
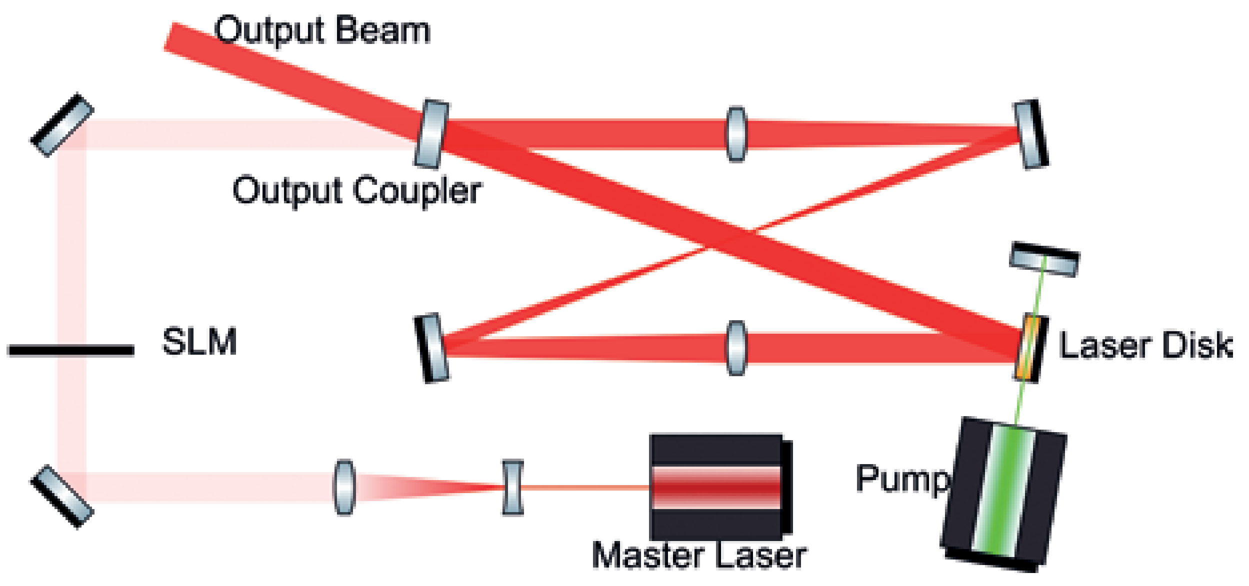


Fig 4: (a) A .stl model of King. The model was then sliced and translated into Gcode (b) A simulation of the 3D-printed piece (c) A King's contour written in fused silica using the Aerotech CNC stage, etched under 60°C for 30h

High Power Image Amplification

Jiho Han



Concept of a laser system for high power image amplification

Previously, a conceptual design for a high power laser system with a dynamic arbitrary transverse beam profile was proposed. The envisaged principle of operation is as follows:

1. Use a low power laser on a spatial light modulator to spatially modulate some beam parameter
2. Inject this shaped beam into a high power laser configured with an input and output port
3. The output beam is as the input beam, just at a much higher power level

Depending on the choice of parameter used, it may require filtering or other transformations to achieve the final desired intensity profile. As a preliminary experiment, available apparatus were put together to gain some insight into the system behaviour and the feasibility of this proposal.

The first part of the experiment was aimed at testing a design for an optical cavity that can amplify a spatially modulated input beam have been proposed and tested. It was found that a cavity arrangement designed for a large number of modes can be used to transmit an arbitrary beam profile, suggesting that such cavity design is likely to be successful for this purpose.

The second part of the experiment was to inject a beam into the cavity so that the forward circulating beam is promoted while the backwards propagation is suppressed, since the backward propagation may damage the spatial light modulator. Though the concept has been demonstrated long ago (Stover and Steier, 1966), the discussion had been traditionally limited to single mode lasers or those with only a few modes. The experiment yielded in some limited evidence that this is possible for multimode lasers, too. It currently appears that the difficulties in mode matching the mode structures of this multi-mode laser are what failed the required operation where the backward propagation is suppressed. Note also, that mode matching is important in its own right, since all modes that are not matched by seed injection will emit at its own 'pace', in an uncontrolled manner.

The last part was to attempt to control the polarization profile of output of the multimode ring laser. With the second part of the experiment failing, it was not possible to perform this part of the experiment properly, but by placing the polarizer at various points of the cavity, it was found that the cavity had some significant polarization preference, suggesting that the polarization cannot be used as the modulated parameter, unless this polarization preference is somehow removed.

The following work on this project will theoretically address the mode matching problem. Once this problem is solved, it is currently believed that all modelling tools required for a full system design is established. Hence the rest of the project is likely to focus on designing and constructing the laser system, as required.

Digital Fabrication using Droplet Deposition and Ultrafast Laser Machining

Yoanna Shams | **Sponsor:** M-Solv Ltd and The Centre for Science Technology and Innovation Policy (CSTI)

The focus of this PhD research is to develop a novel manufacturing method for high resolution digital patterning of functional materials for niche, low volume applications such as sensors and responsive devices. The underlying techniques include digital liquid deposition coupled with studies into post deposition processes such as (i) digital control of surface wettability and (ii) ultrafast laser fabrication. The manufacturing challenges and future capability of the hybrid technology will also be researched by understanding key scientific aspects and challenges of:

a) Droplet and surface interactions

b) Functional material and laser compatibility

Initial Research

The initial research will focus on compiling a comprehensive literature review on the controlled delivery of microscale droplets with advanced functional materials to a range of glass and polymer surfaces, changing surface wettability and post patterning of resulting functional films. The main focus of study will be digital, non-contact technologies to modify surface reactivity and chemical functionality. This includes inkjet, spray, nebulizers and digital laser-based lithography. These non-contact, digital techniques are essential due to the need for flexible manufacturing and handling of fragile, surface-sensitive materials. Experiments will commence by examination of inkjet printing of nanomaterial inks, printing of fine structures and subsequent ultra-precision ablation to explore changes in material function.

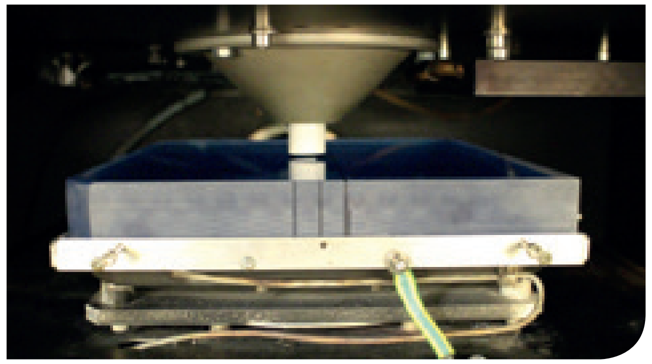
The U.S. Department of Defence's Manufacturing Technology Programme has developed a framework looking at Manufacturing Readiness. This is a detailed, interactive tool that will be a starting point to drive a UK-focused examination of our manufacturing challenges and what we can do to de-risk the process at an early stage. Yoanna will be closely integrated into this activity with The Centre for Science Technology and Innovation Policy (CSTI), both through interviewing academic and industrial leaders about tackling manufacturing challenges but also through using the tool to guide experimental research.

Laser Assisted Reactive Atom Plasma Processing for Ultra Precision Engineering of Space Optics

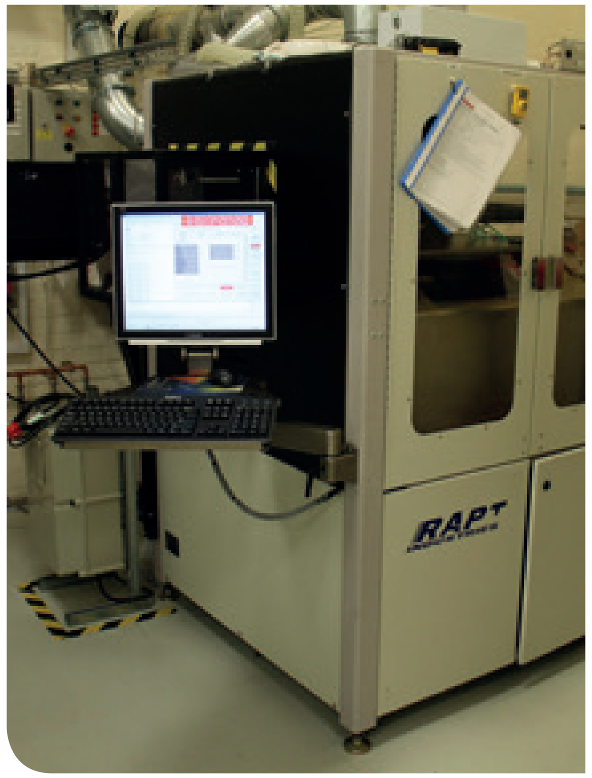
Adam Bennett | **Sponsor:** Gooch & Housego

Advances in acoustic optical devices demand higher quality surface finishes; these systems need to have greater resolution, thus optical systems need to be fabricated from new techniques that can offer the high form accuracy that is required. The proposed method to achieve this is by a new energy beam process.

This energy beam process involves activating a plasma whereby controllable sized laser beams could be injected into the plasma region to create a material removal process having high processing speed and nano-meter levels of control.

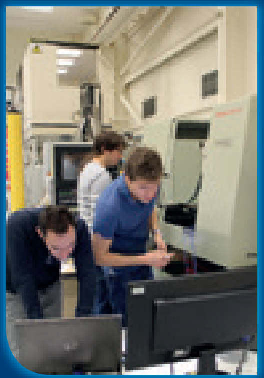


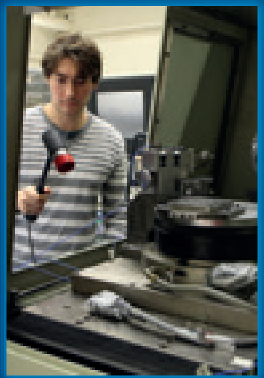
Plasma torch with fused silica substrate



RAP300 Plasma figuring machine

Centre for Doctoral Training





The Centre for Doctoral Training in Ultra Precision is now delivering its final cohort from phase 1 and is currently recruiting students for phase 2 which starts in October 2015. The phase 2 extension was awarded in March 2014, under grant reference EP/L016567/1. The new award will further strengthen the research activity within the EPSRC Centre for Innovative Manufacturing in Ultra Precision at Cambridge and Cranfield Universities.

Phase 1 of the Centre for Doctoral Training is completing its final set of three funded cohorts, of 24 students in total. Phase 2 will consist of 4 cohorts of 10 students, with applicant access ports from Cranfield University and Cambridge University. The new award has a total value of £6.2M and will run until 30th September 2022.

The Centre for Doctoral Training will continue to develop its leading training and research environment that will deliver to industry highly skilled ultra precision engineers capable of making a significant impact on the ultra precision industrial landscape. The collaborating team from Cambridge and Cranfield Universities will increase the range of research topics and widen the participating University supervisors through strengthened Centre collaborations across the Cambridge Departments of Material Science and Chemistry and the Ultra Precision laboratories and unique facilities across Cambridge and Cranfield. New training programmes will be delivered by the National Physical Laboratory that will enhance the research skills and experiences in advanced metrology. This will provide the students with an unequalled practical foundation in ultra precision processes and technologies.

The Centre for Doctoral Training and the EPSRC Centre in Ultra Precision has a growing cohort of 30 ultra precision engineering PhD students across the two universities and other UK universities engaged in ultra precision related research. This is set to increase to around 70 by the end of the final year in 2022. We have established a proven alliance of highly complementary institutions. A partnership reinforced by relationships built in previous co-operations between investigators through EPSRC funded Grand Challenges, IMRC and IKC programmes.

In addition to providing excellent research and skills training, the Centre provides education in innovation and translation of research output. This aspect is recognised as being critical to the commercial success of the EPSRC and industry funded research. We have established strong links between students from the EPSRC Centre in Ultra Precision and EPSRC funded programmes in the Centres for Innovative Manufacturing in Large Area Electronics, Laser Based Production Processes, and the Graphene Engineering Centre.

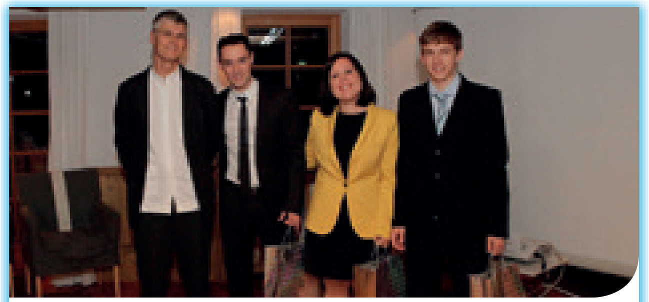
Awards and Prizes

Andrew Payne

Andrew Payne, PhD researcher of the Centre for Industrial Photonics at the University of Cambridge was one of the winners of the Department of Engineering's annual photo competition. The annual competition, sponsored by Zeiss, aims to show the breadth of engineering research at the University, from objects at the nanoscale all the way to major infrastructure.

Andrew won the Head of Department's Prize for his video of the rise and fall of liquid crystal 'mountains'. The video was made from a collection of images taken at one-second intervals. It shows the slow growth of liquid crystal structures under the influence of an alternating electric field, and their rapid collapse as the field is reversed.

The video can be viewed here:
https://www.flickr.com/photos/cambridgeuniversity-engineering/13958088817/in/set-72157644383738382



Team Hertz (left to right) Dr Wolfgang Knapp (euspen President), Jonathan Abir (Cranfield University, UK), Veronica Iacovacci (Scuola Superiore Sant'Anna, IT), Tomas Lazak (Czech Technical University, CZ)

Jonathan Abir

eu**spen** Challenge is an annual international competition held by eu**spen** identifying students with potential to be future leaders in the field of precision engineering and nanotechnology. eu**spen** and HEIDENHAIN GmbH hosted thirty European and international students 1-3 July 2014 in Traunreut, Germany. Students were placed into ten teams and provided with a set of limited materials, tools and test equipment to help build a proto-type within twenty four hours. The challenge was to solve a problem of trembling hands associated with using a laser pointer.

Jonathan Abir, one of the Centre's PhD researchers represented Cranfield University. He was part of winning Team Hertz who were awarded the Best Presentation and Most Innovative Solution. Jonathan said "I relished the task of working with other students to solve a technical challenge with real life applications!"

Left to right: Prof Ian Hutchings (poster judge), Denise Chappell (poster judge), Jessy Zhou (joint second prize winner), Tianqi Dong, Jon Parkins and Prof Sir Mike Gregory (Head, Institute for Manufacturing)

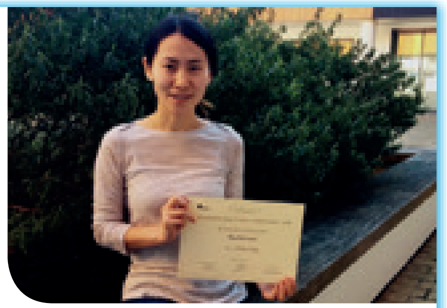
Jon Parkins and Tianqi Dong

The First Year PhD Conference is an event which aims to help PhD students at the Institute for Manufacturing (IfM), University of Cambridge, develop transferable skills such as project management, public speaking and event planning, which will be useful in their career. The conference is organised and run by the first year PhD students at the IfM and features talks and posters from the PhD students which are then judged by a panel of experts.

PhD student Jon Parkins, supervised by Prof Bill O'Neill, was the poster winner at the May 2014 conference for his research on Increasing Throughput of Laser Additive Manufacturing in Metal Powders for Biomedical Applications.

Joint second place went to Tianqi Dong, also supervised by Prof Bill O'Neill for her research on Femtosecond Laser Direct Micro-Cutting of Graphene for Device Applications.

Tianqi Dong with the Roger Kelly Award



Tianqi Dong

Tianqi Dong, a PhD researcher based at the IfM, University of Cambridge was presented with the Roger Kelly Award for Best Young Research Presentation after coming third place at the 4th International School on Lasers in Materials Science (SLIMS) held in Venice, Italy from 13-20 July 2014.

Tianqi's 10 minute presentation Femtosecond Laser Direct Micro-Cutting of Graphene for Device Applications was aimed at a scientific and professional audience (18 Professors) and there were also questions and discussions during a poster session. Winning joint second place at the First Year PhD Conference at the IfM in May 2014 allowed Tianqi to gain the experience and confidence to compete at international level.

Quality and Metrics

	Target	Achieved at Year 3 point
Publications		
Journal papers 1 paper per 1 research staff person year	55	48
Keynotes given by Centre investigators and researchers 1 keynote given at international conference per 2 staff person years	25	17
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 UP Centre as UK hub	15	14
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	4
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	8
Uptake		
Centre main project taken forward by industry	3	2
Centre		
Planning and delivery Hold overall programme by delivering Gantt deliverables and milestones	22	11
Added value to UP Centre Secure additional funding equal to EPSRC original funding	£6.8m	>£7m

Centre Publications

Journal Publications

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Appendices

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