UNIVERSITY OF CAMBRIDGE

IfM Education and Consultancy Services

Roadmapping Workshop for the EPSRC Centre for Innovative Manufacturing in Ultra Precision

REPORT

Micro-Manufacturing Research Platform

The Workshop was sponsored by EPSRC

22 April 2015

Report drafted by Dr Nicky Athanassopoulou at IfM ECS

1. Executive Summary

The EPSRC Centre for Innovative Manufacturing in Ultra Precision organised a roadmapping workshop for the Meso research technology platform (also called Micro-Manufacturing) on 22 April 2015 at Cranfield University. Eight industrial participants contributed to the workshop, whose aims were to:

- Identify applications that are emerging in ultra precision engineering that would benefit from the technological advancements made in the Meso research platform.
- Understand the Micro-Maching manufacturing process and discuss the capabilities of the new Meso machine as an example.
- Identify the industrial products and services that may be enabled, fit into or benefit from Micro-Machining.
- Explore the best applications in the Meso platform, their value for UK businesses and the best route for their commercialisation.

This workshop followed on from a previous workshop that took place in October 2011 for the whole EPSRC Centre in Innovative Manufacturing in Ultra Precision.

The main **markets** that micro-manufacturing can have relevant applications were the following:

- Security
- Industrial applications
- Consumer
- Light/Optical applications
- μ-fluidics
- Semiconductors
- Large science projects
- Other

The three **priority applications** identified were:

- Small format micro-manufacturing machine for the retail opticians
- Large science projects e.g. CLICK
- μ-fluidic device application

The μ-fluidic device application was not explored further as there were not any industry experts from this domain in the workshop.

The most important **actions** required to deliver these applications were:

Application 1: Retail Machine

- Perform a technical feasibility study for the retail machine application
- Develop a business proposition that includes a cost model for a basic retail machine and understand the reliability requirements of such an application

Application 2: Big Science projects

- Introduce vacuum processes
- Develop IBF
- Introduce ability for applying coatings
- Understand what is the benefit of 6-axes
- Develop the following key technologies/ research:
    - Air bearings
    - Free form nanometric technology
    - Software for environmental characterisation and compensation

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2. Methodology

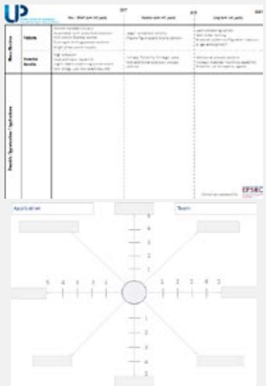
The workshop methodology consisted of three parts: a **Design and Pre-work** part, the **Workshop** and the **Analysis and Client Report**.

1. The **Design and Pre-work** consisted of the following activities:

(a) confirmed with the workshop sponsors the key aims and desired outputs from the workshop;

(b) designed the appropriate roadmap architecture and group templates;

(c) designed the workshop process and required collateral material for the workshop (facilitation slides, participant handouts, etc).



2. The one-day **Workshop** brought together eight participants from industry. The workshop aims were to:

(a) present each participant's input on the future applications in ultra precision for micro-manufacturing;
(b) prioritise the applications using pre-defined selection criteria;
(c) select the most suitable micro-manufacturing applications to explore further;
(d) explore the shortlist of manufacturing applications in groups and determine the performance targets required, the desired technology development plans to reach the performance targets and identify the most important R&D priorities.

3. The final part consisted of the transcription of all output from the workshop into an electronic format, content analysis and the drafting of the **Client Report**.

The report can be used by the workshop sponsors for setting research priorities and, if appropriate, communicating these with academic, industrial or public sector stakeholders.

3. Background and Previous Work

The EPSRC Centre for Innovative Manufacturing in Ultra Precision aims to create ultra high precision manufacturing processes and tools that can make products with nanoscale precision. The Centre fosters and accelerates the development of emerging high value products through its dedicated production compatible ultra precision process research platforms and internationally leading research programme.

Through a close interaction with UK precision manufacturing supply chains, the UK's emerging product developers and leading international organisations, the Centre has established a unique world–leading, UK based ultra precision research centre. The Centre was established in 2011 and in October of that year it conducted a workshop to roadmap the market and industry drivers and future applications in ultra precision.

The Centre conducts research in three technology platforms; Nano-FIB, Meso and R2R. The initial workshop in October 2011 mapped all three platforms in parallel, reviewed key trends and drivers and identified future applications, which could result in novel Production Machines and Products and enabling technologies to support these.

The original roadmap developed for the Centre is shown below:

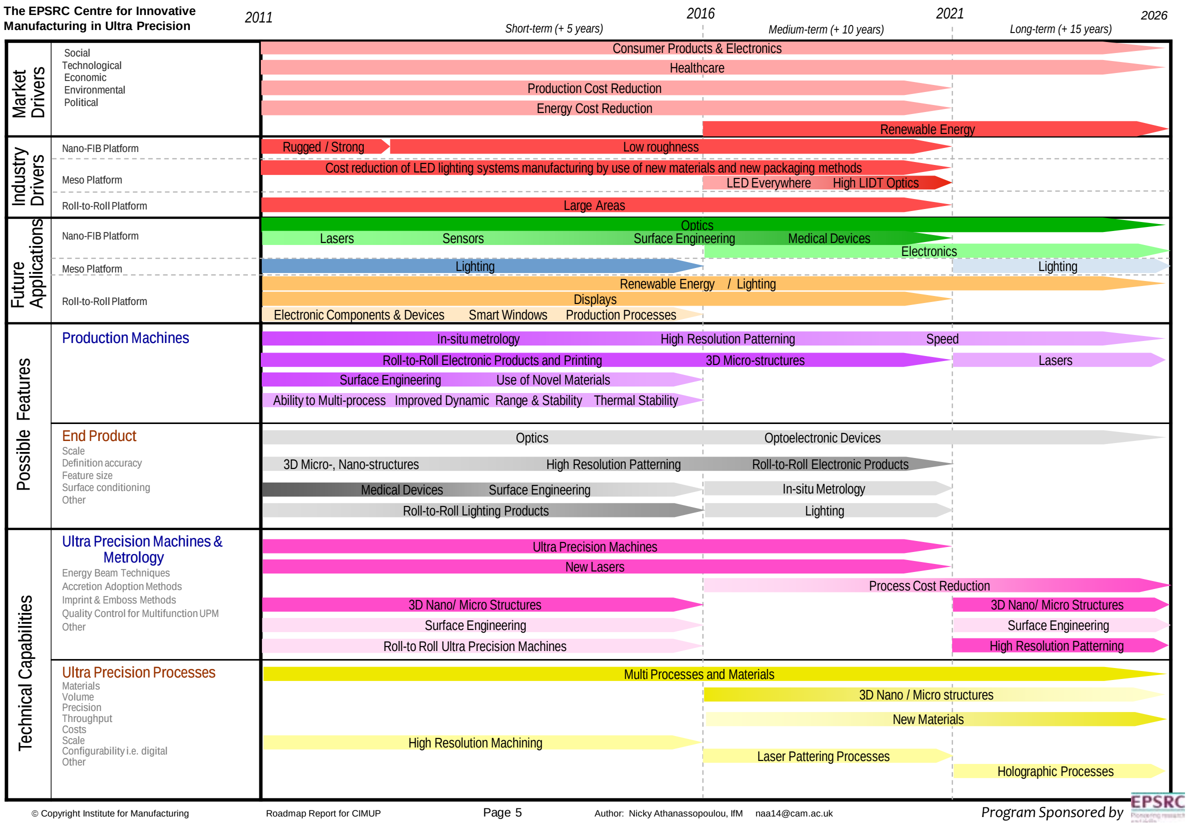


***Figure 1** – Original Roadmap for the EPSRC Centre in Ultra Precision (Oct 2011)*

The three technology platforms were also explored in more detail during that workshop to establish required targets, technology developments and knowledge gaps, enablers and drivers. The summary plan derived for the Meso research platform is shown below.

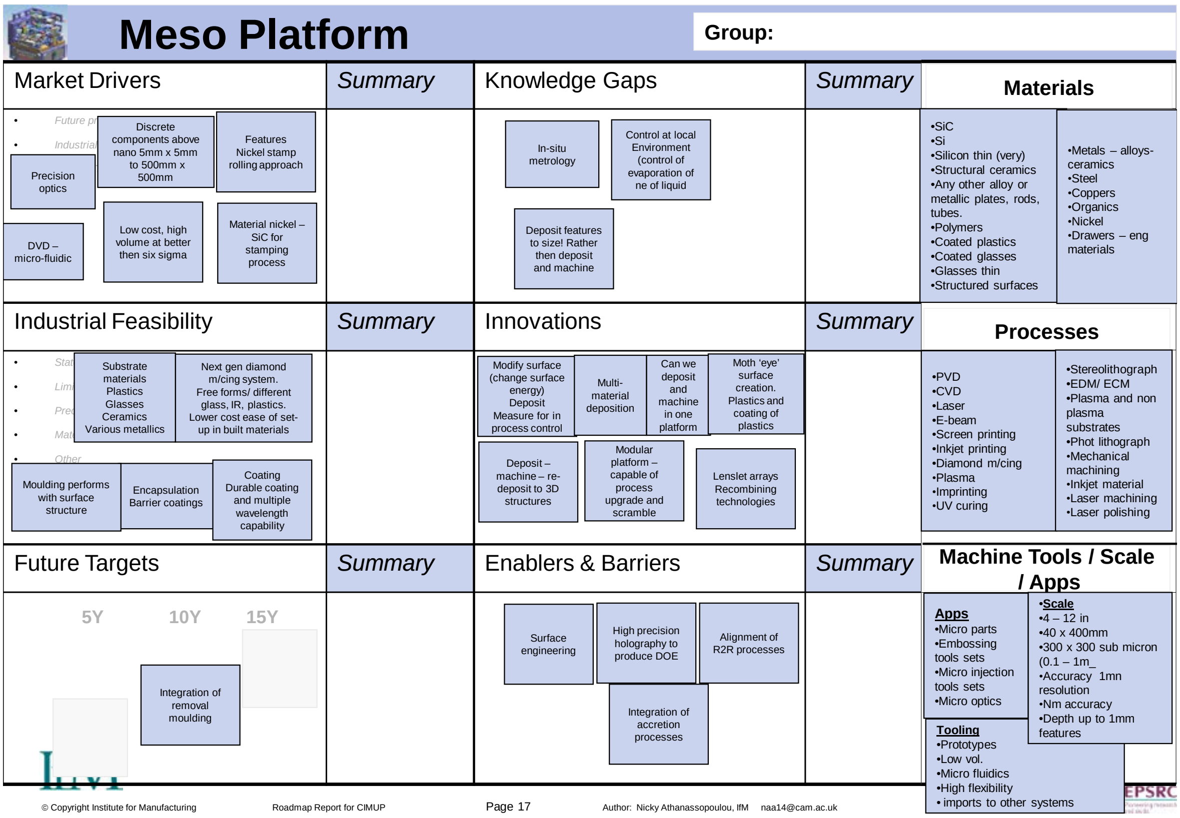


***Figure 2** – Original exploration of Meso technology platform for the EPSRC Centre in Ultra Precision (Oct 2011)*

Considerable technological development has taken place since then in all three research platforms. The Centre now has developed micro-manufacturing technologies and a micro-machine and would like to develop an innovation roadmap for its Meso research platform to explore potential applications for the technology.

4. Current capabilities of the Micro-manufacturing research platform

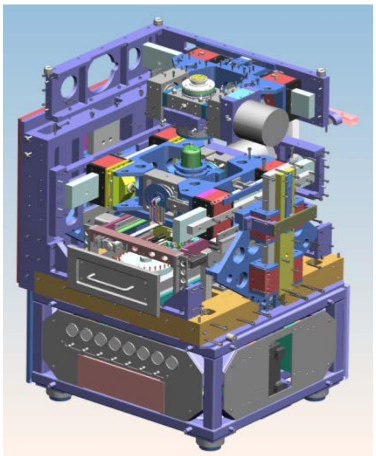
Great progress has been achieved in the Meso research platform since 2011. The Centre can now showcase a compact, 'white goods' sized Meso-machine that is effectively a micro-factory capable of a range of subtractive and additive processes. Specifically the Meso-machine demonstrates a number of key technologies such as:

- Robust modular design
- Multiple machine configurations (not necessarily a reconfigurable machine)
- Alternative motion technologies selected as appropriate to process
- Multiple process capability in each machine

Additional and separate capabilities also shown are:

- Diamond machining (turning/milling)
- Beam processing (RAPT/Laser)
- Imprint, Embossing, inkjet/lacquer application, UV curing

This Meso-machine is a new generation of high performance ultra precision manufacturing system. A schematic of the Meso-machine is shown in the figure below.



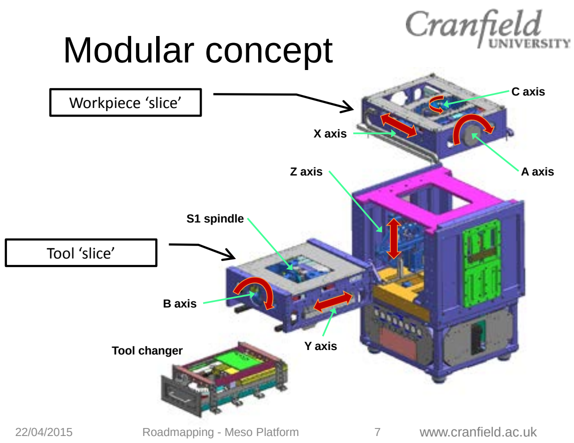


Figure 3 *– Current Meso-machine design developed by Cranfield University*

The capabilities of the new Meso-machine can be used for the mass production of a variety of high precision applications, such as:

- watch components
- inkjet printing components
- IR and integrated optics
- Moulds
- medical and microfluidic devices
- optical components

The workshop was organised in order to expand the potential application list and prioritise the ones that appear the most promising in order to focus future research and commercial plans.

5. Meso Roadmap Summary

The roadmap covers three time periods: the short term (+2 years i.e. up to 2017), the medium term (+3 years i.e. up to 2018) and the long term (+5 years i.e. up to 2020). Eight people from both industry and academia contributed with content for its creation.

The roadmap includes two broad layers; (1) Micro-Manufacturing Features and Benefits, and (2) Possible Opportunities/Applications. The **Possible Opportunities/Applications** section was further subdivided into the following layers:

- Security
- Industrial applications
- Consumer
- Light/Optical applications
- μ-fluidics
- Semiconductors
- Large Science projects
- Other

In total, 38 possible applications were identified. All but two applications were in the short and medium term. The Industrial Applications and Light/Optical Applications were the two most populated sub-layers.

A schematic of the roadmap is shown below.

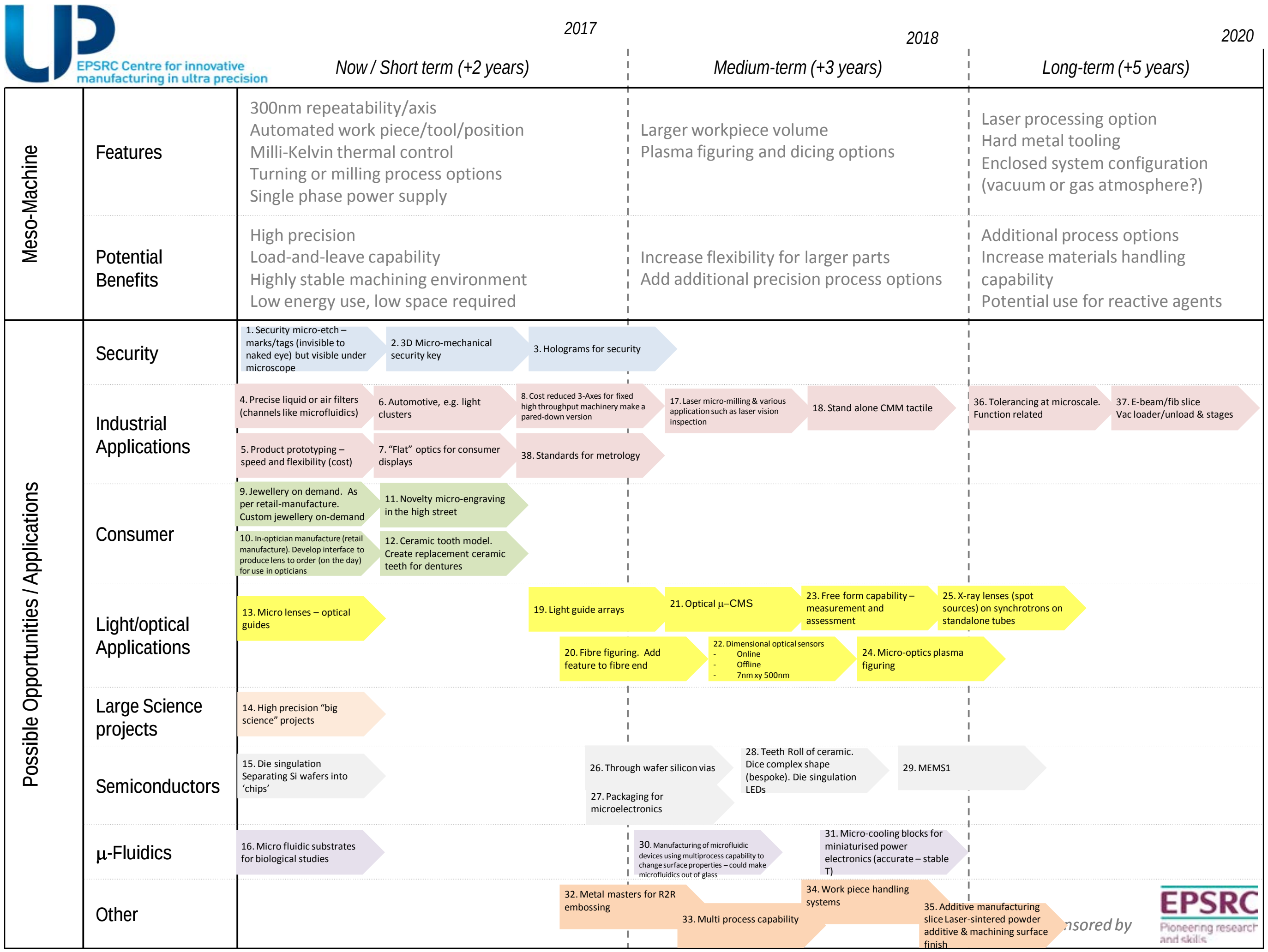


Figure 4 *– Roadmap of possible applications for the Ultra Precision Meso research platform*

6. Prioritisation of Possible Applications

Each of the 38 applications put forward during the workshop was assessed using two different and broadly separate considerations: Opportunity and Feasibility. Opportunity was defined as the magnitude of the opportunity plausibly available to an organisation. Feasibility was defined as how well-prepared the organisation is to grasp the opportunity.

The Opportunity and Feasibility criteria had been selected in advance of the workshop by the Centre, and are shown in the figure below.

Selection Criteria for CIMUP – Meso

FACTOR	DEFINITION
Market size	Size of potential market, or number of potential adoptions, reasonably available to us.
Industry / market readiness	How easy will it be for customers or adopters to take up the product or process; do they have to change their behaviour or processes?
Future potential	Product is a platform for future products or could open new markets in future

FACTOR	DEFINITION
Technical challenge	How confident are we that the proposed product is technically feasible?
Technical Capability	Do we have the required technical competence to design the product?
Fit to manufacturing and/or supply chain	Ability to manufacture or supply the product
Market knowledge	Our understanding of size and requirements of the market

Figure 5 *- Opportunity and Feasibility criteria used to assess the different Meso applications*

The assessment process took place in two parts. Firstly, each participant was asked to review the 38 applications and independently select four to eight, based on the three Opportunity factors. The participants placed their votes on the actual post-its using eight green sticky dots. Participants were discouraged from voting for the applications they had contributed unless they were part of bigger group or cluster.

In the second step, participants were asked to consider only applications that had already received Opportunity (green) votes. Each participant was then asked to independently select two to four applications based on the four Feasibility factors. The participants placed their votes on the actual post-its using four yellow sticky dots.

A shorter list of 15 applications (shown in the table below) was thus derived and considered further during the workshop. This shorter list still contained applications from all sub-layers of the roadmap.

Application	Feasibility	Opportunity
32. Metal masters for R2R embossing	5	6
14. High precision "big science" projects	4	4
30. Manufacturing of microfluidic devices using multi-process capability, e.g. mechanical & plasma treatment to change surface properties – could make micro-fluidics out of glass	4	4
10. In-optician manufacture (retail manufacture). Develop interface to produce lens to order (on the day) for use in opticians	3	4
1. Security micro-etch – marks/tags (invisible to naked eye) but visible under microscope	2	3
3. Holograms for security	2	5
4. Precise liquid or air filters (channels like micro-fluidics)	2	3
13. Micro lenses – optical guides	2	3
31. Micro-cooling blocks for miniaturised power electronics (accurate – stable T)	2	1
15. Die singulation. Separating Si wafer into 'chips'	1	2
16. Micro fluidic substrates for biological studies	1	3
21. Optical μ-CMS	1	2
24. Micro-optics plasma figuring	1	3
26. Through wafer silicon vias	1	4
28. Teeth, Roll of ceramic, Dice complex shape (bespoke), Die singulation LEDs	1	2

Table 1 *- Shortlisted applications including the Feasibility and Opportunity votes for each application*

The shortlist was transferred onto a 2x2 matrix with Opportunity shown on the vertical axis and Feasibility on the horizontal axis (see figure below). This was to facilitate decision making and the selection of the most appropriate applications to explore during the workshop. Applications placed on the top right quadrant (High Feasibility and High Opportunity) were of immediate interest. Applications on the top left quadrant (Low Feasibility and High Opportunity) may represent possible long-term opportunities. Applications placed on the bottom quadrants (Low or High Feasibility and Low Opportunity) are not automatically dismissed as they might enable other applications or support longer-term prospects.

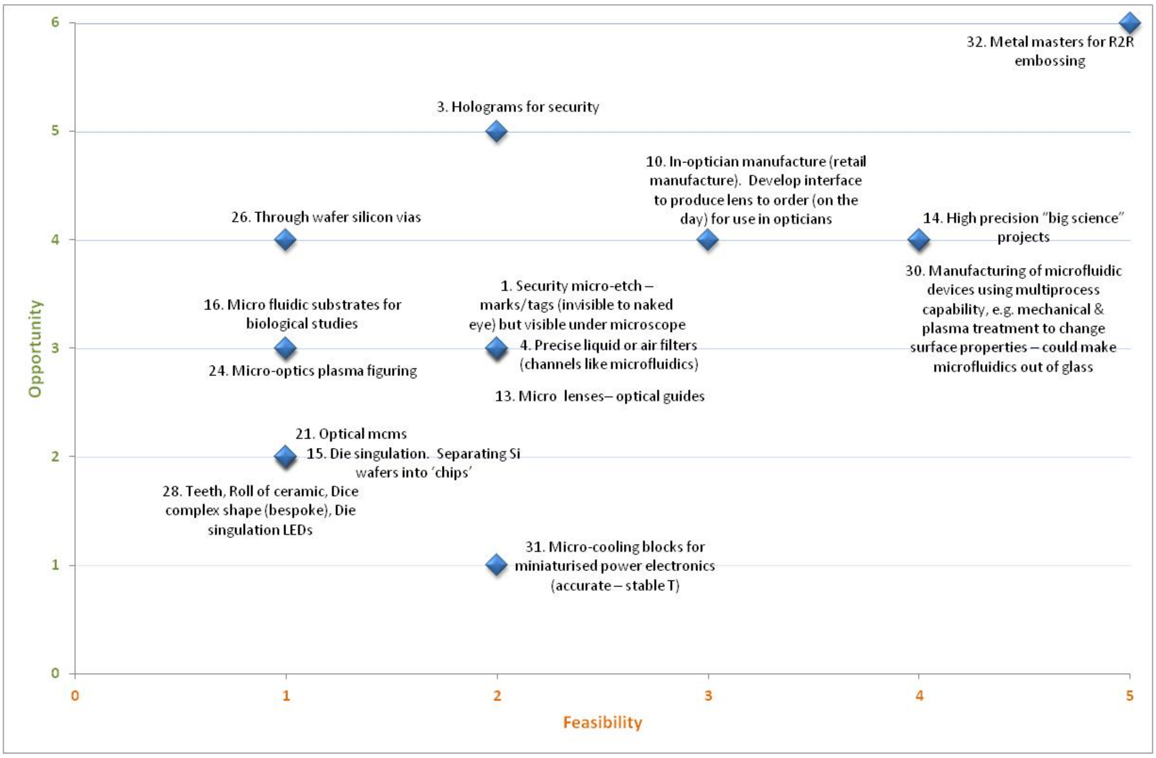


***Figure 6** – Application prioritisation chart using Feasibility-Opportunity axis*

All participants were involved in choosing which of the applications were most appropriate to take forward. The selection process was done by consensus. It took into consideration the following aspects to achieve a balanced selection:

- the requirement of the application for high volume, precision manufacturing of components;
- relative scores of each application and their position onto the 2x2 chart;
- the specific expertise and interest of the workshop participants;
- the sub-layer or category for each application;
- the timeline of the application (short, medium or long term).

The following two applications were selected for further exploration:

1. **"10. In-optician manufacture (retail manufacture). Develop interface to produce lens to order (on the day) for use in opticians"**

2. **"14. High precision "big science" projects"**

Project *"32. Metal masters for R2R embossing",* although the highest scoring, was not selected as this particular application is currently addressed by research conducted at a different university. Project *"30. Manufacturing of microfluidic devices using multi-process capability, e.g. mechanical & plasma treatment to change surface properties – could make microfluidics out of glass"* was initially selected for further exploration as it was both scientifically and commercially interesting but it was dropped shortly after as none of the participants had specialized knowledge on this particular application.

7. Exploration of the Two Future Applications

Each application was explored in four steps. Initially, the scope and boundaries of the application were considered as well its required performance parameters. The current performance parameters were then explored and compared to those of the main competitive technology. The technologies and research required to improve the application's performance were then discussed and agreed upon including any milestones, success factors and knowledge gaps and are required to realise the final vision. Finally, the key actions needed to commercialise the application were summarised.

The participants were split into two groups, each exploring one application. The following people participated in each group:

Application 1: Retail Machine	Application 2: Big Science projects
Mike Cooke Paul Everitt Ian Holton Paul Morantz	Claudio Giusca Marco Castelli Martin O'Hara Alison Raby

***Table 2** – List of attendees participating in the exploration of the two selected applications*

The high-level roadmaps are shown below. These include the following fields:

- Detailed description of the application and its performance requirements
- Scope and boundaries of the application indicating aspects that are included and excluded from further development
- Desired milestones for a top level development plan
- Required technology, research and/or capabilities for each milestone
- Any key success factors or important knowledge gaps that need to be addressed
- Specific actions and commercialisation steps required to assist further development of the application

The performance requirements needed for each application are also shown in the figures below. Each performance parameter is rated on a scale from to 1 to 5, with 1 indicating poor performance and 5 excellent performance.

Application 1: **Retail Machine**

Description:	**Performance Requirements:**
• **A Fresnel spectacle 30% less weight than conventional specs at the same cost** • **The lens must “look thin”** • **Can we use lower cost, lower RI material?**	• Operating cost for the machine • Cost of machining a pair parity • Lens thinness • No cutting lubricant or easy-fill/clean lubricant • Self-calibrating. No expert set up • Target time to produce pair of lenses – 20 minutes • Fully customisable per-prescription glasses • Produce lighter lenses

			Now	**Short term**	**Medium Term**	**Long term**
Step 2: Roadmap for the Application	**a. Milestones**			Feasibility study • Technical • Business proposition	Develop retail machine Pilot	Launch
	b. Required Technology / Research / Capabilities	Need to understand:	• How do you work from an optician’s prescription to a milling pattern? • Front/rear face anti-reflection coating • Physical optics evaluation • Are Fresnel optics better/worse than conventional? • Aberrations better/worse? • % loss of field of view? Viewing experience? • Ability to overcoat Fresnel surface • How do you design a Fresnel lens with an acceptable viewing experience? (Dead spots? Discontinuation ?) • Is it possible to clean a Fresnel surface as easily as current specs?	• Cost model for a ‘”simple” tool • Qualify reliability		

***Figure 7** - Roadmap for the Retail Machine application*

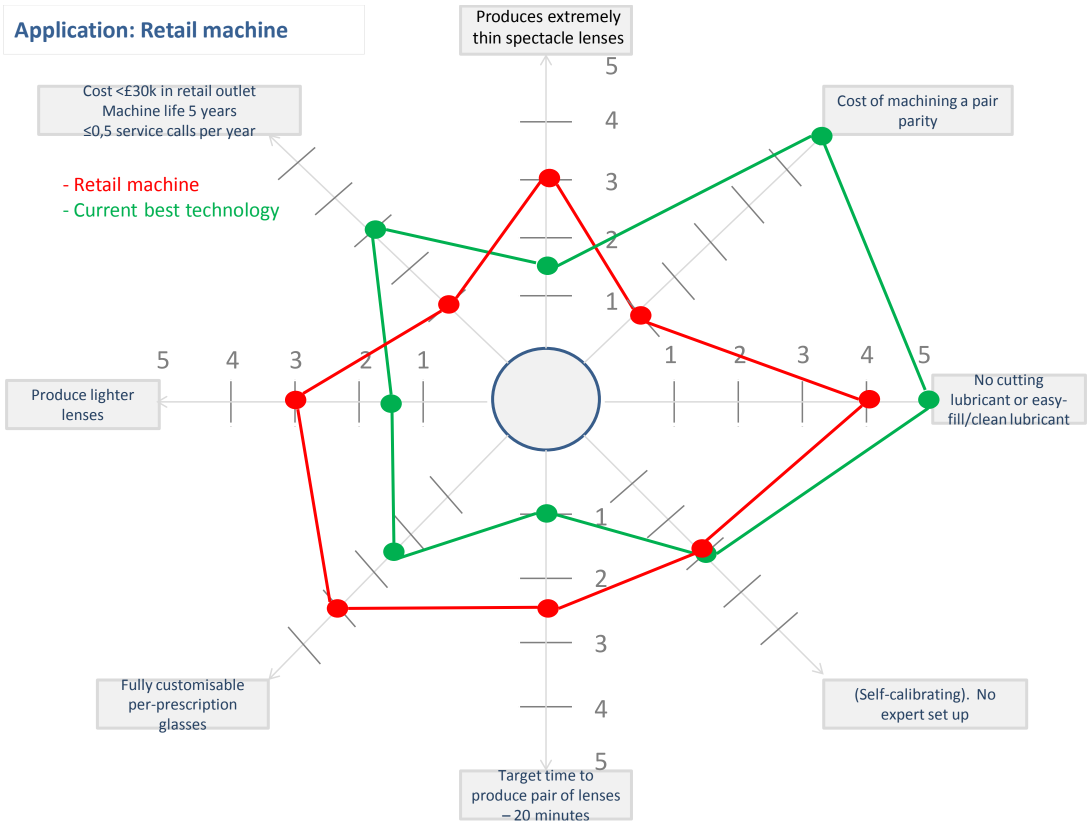


Figure 8 *– Current performance comparison between the ultra precision Retail Machine and current technology*

Key performance gaps for the retail machine were the costs for producing the product as well as the expected acquisition and operating costs for the machine. It had clear advantages of producing much thinner, lighter, fully customised lenses more quickly than current alternatives.

Application 2: **Big Science Projects – Example CLIC**

Description:
An example is CLIC at CERN. Other possible big science projects are ESA at NASA, NIF, ITER at JET, High energy laser (DE) and Synchrotrons & light sources

- **Surface form - µm**
- **Finish – nm**
- **Material – cv**
- **Milling and turning throughput > IMRS**

Performance Requirements:

- Surface form - µm
- Finish – nm
- Material – cv
- Milling & turning throughput > IMRS
- Nanometer – sub nm
- Optical - finish

Step 1: Scope

What's IN

1) Way to develop new technology (funded)
2) Force innovation around core capability
3) Profile building
4) Niche
5) Military also linked
6) Registration, higher & higher precision optics, gratings, up(?) metal surfaces
7) Materials/environment

What's OUT

1) Exposing IP?
2) Does it produce a standard product?
3) Niche/loss leader
4) Long lead times

Step 2: Roadmap for the Application

		Now	**Short term**	**Medium Term**	**Long term**
a. Milestones		Understand what is the benefit of 6-axes	What we have	Air bearings	Thermal compensation (active to compensate for ext temp etc)
b. Required Technology / Research / Capabilities	Surface finish mill turn	<1 mm RMS	3-4 µm 6 nm	1 µm 1 nm	<1 µm 1 nm
	Form accuracy	0.5 µm PV	2 µm	0.5 µm	<0.5 µm
	Environmental isolation	±1°C 50% RH 300 Hz	±1°C 50% RH 150 Hz	±1°C 50% RH ?	Uncontrolled ? 300 Hz
	Lack of CAD/CAM interface	IGES, STEP, STL etc	Manual	Own conversion	Auto conversion

c. Success Factors

- Dissemination – networking – publication conferences
- Advocate clients
- Complex mathematics
- Remove an axis?

c. Knowledge Gaps

- How do we recognise opportunities and upcoming big science projects?
- Tenders and bidding process
- Inertia to incumbent supply chain
- CAD/CAM tool interface

Step 3: Next Commerci-alisation Steps

- < Vacuum processes, IBF, coating

First Actions

- Understand what is the benefit of 6-axes?
- Key technologies/ research required:
  - o Air bearings
  - o Free form nanometric technology
  - o Software for environmental characterisation & compensation

Figure 9 *- Roadmap for the Big Science projects application*

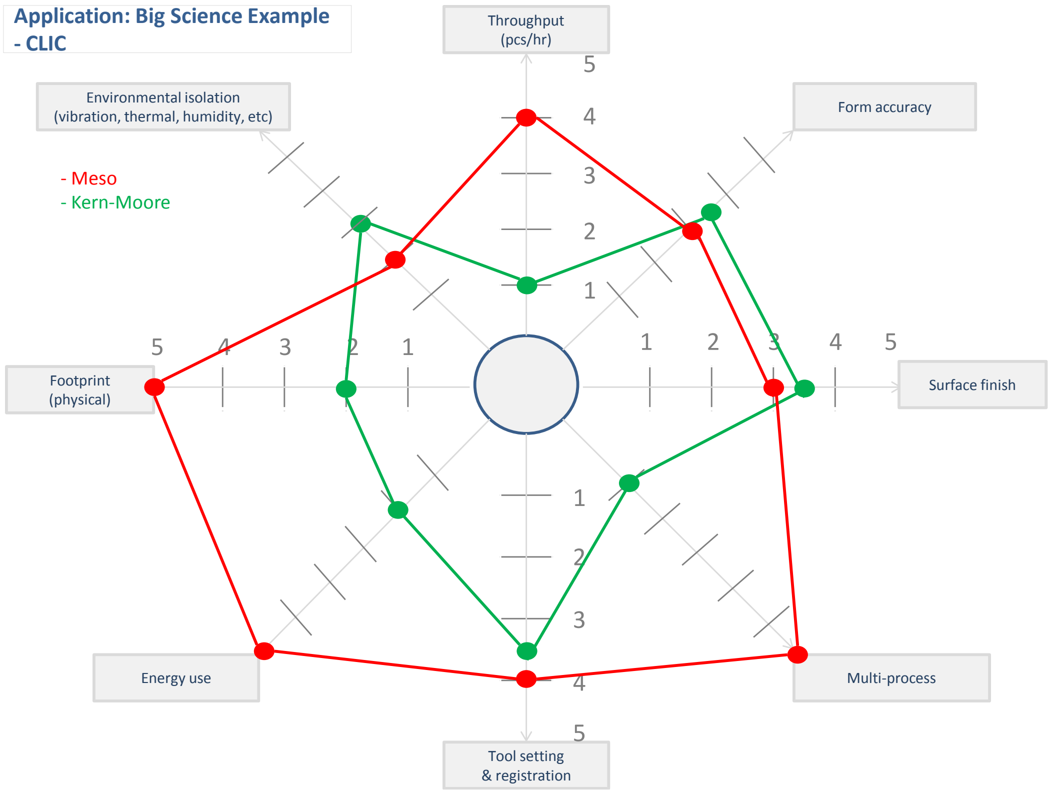


Figure 10 *– Current performance comparison between the Meso-Machine capability and the competitive Kern-Moore technology*

There were no major performance gaps between the new meso machine and the main competitor, Kern-Moore, for producing high precision components. On the contrary, the meso machine outperformed the current alternative technologies in overall footprint, throughput, multi-process capability and environmental performance.

8. Knowledge Gaps and Enablers and next Commercialisation steps and actions

The knowledge gaps identified were both technical and commercial and related to technical feasibility of the proposed applications and a better understanding of the market requirements.

The enablers were also technical and commercial with emphasis to the unique knowledge acquired so far from the meso research platform and the potential to network widely and promote these capabilities to interested market sectors.

The table below summarises the knowledge gaps and potential enablers identified.

Knowledge Gaps
Commercial • How do we recognise opportunities in upcoming big science projects? • How to write tenders and what is the bidding process? • Inertia to incumbent supply chain
Technical • How do you convert an optician's prescription to a milling pattern? • How do you apply front/rear face anti-reflection coating? Is there an ability to overcoat a Fresnel surface? • Are Fresnel optics better/worse than conventional? • Are aberrations better/worse in the lenses? • What is the % loss of field of view? • What is the viewing experience of a Fresnel lens and how it compares to that of conventional lenses? • How do you design a Fresnel lens with an acceptable viewing experience? (Dead spots? Discontinuation?) • Is it possible to clean a Fresnel surface as easily as current specs? • Lack of CAD/CAM tool interface in current design of the meso machine
Enablers
Commercial • Ability and opportunity to disseminate widely – networking – publication conferences • Advocat clients
Technical • Complex mathematics and ability to protect knowhow • Remove an axis may facilitate the use of the meso technology?

***Table 3** – Knowledge gaps and enablers for the ultra precision in Meso research platform*

The next actions were proposed for developing further these applications and facilitating their commercialisation:

Application 1: Retail Machine

- Perform a technical feasibility study for the retail machine application
- Develop a business proposition that includes a cost model for a basic retail machine and understand the reliability requirements of such an application

Application 2: Big Science projects

- Introduce vacuum processes
- Develop IBF
- Introduce ability for applying coatings
- Understand what is the benefit of 6-axes?
- Develop the following key technologies/ research:
    - Air bearings
    - Free form nanometric technology
    - Software for environmental characterisation and compensation

9. Conclusions

A roadmapping workshop organised and sponsored by the EPSRC Centre in Innovative Manufacturing in Ultra Precision for the Micro-manufacturing research platform was held on 22 April 2015 at Cranfield University. The Centre wanted to identify potential applications that can be enabled and/or benefited by the technological advancements made in the Meso research platform and explore the most suitable ones.

The workshop brought together eight participants from industry and academia in the UK to identify and prioritise relevant applications and assist in developing future development steps for these applications.

Three **applications** were selected as priorities due to their requirement for high volume manufacturing of high precision components and their relevance to the Centre's key research objectives:

- Small format micro-manufacturing machine for the retail opticians
- Large science projects e.g. CLICK
- μ-fluidic device application

The μ-fluidic device application, although very interesting, was not explored further as there were not any industry experts from this domain in the workshop.

The most important **actions** required to develop these applications were mainly technical and a few commercial. These are summarized below:

Technical developments required:

- Perform a technical feasibility study for the retail machine application
- Develop and implement vacuum processes into the meso-machine
- Develop the capability to applying coatings with the meso-machine
- Develop air bearings
- Develop IBF
- Free form nanometric technology
- Develop software for environmental characterisation and compensation

Commercial developments required:

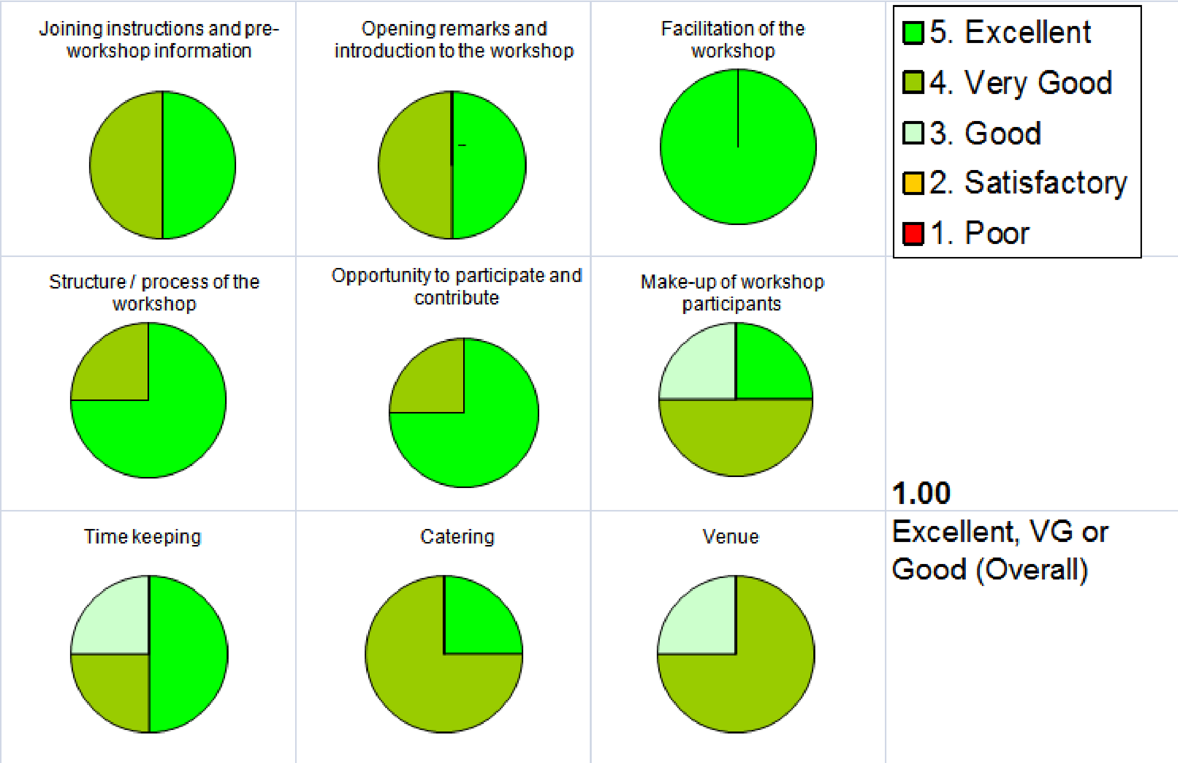
- Develop a business proposition that includes a cost model for a basic retail machine and understand the reliability requirements of such an application
- Understand if there is a benefit in the use of 6-axes and for which specific components or applications

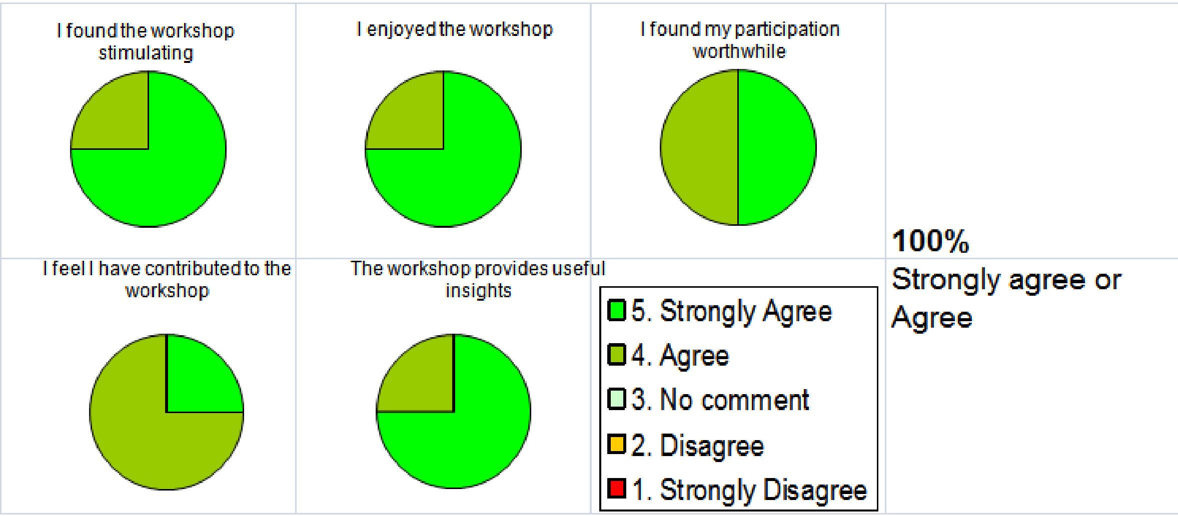
10. Appendix 1 – Participants List

Surname	Name	Organisation
Athanassopoulou	Nicky	IfM ECS, University of Cambridge, Facilitator
Castelli	Marco	Loxham Precision
Cooke	Mike	Oxford Instruments
Everitt	Paul	Goodfellow Cambridge Ltd
Giusca	Claudiu	National Physical Laboratory
Hirose	Yuta	IfM, University of Cambridge
Holton	Ian	Acutance
Morantz	Paul	Loxham Precision
O'Hara	Martin	Cranfield University
Raby	Alison	Elektron Technology

11. Appendix 2 – Participant Feedback

Feedback was received at the end of the workshop from 4 participants. 100% considered the workshop to be Excellent, Very Good or Good as well as useful and stimulating. All considered their participation worthwhile. The detailed feedback is shown below.





12. Appendix 3 – Workshop agenda

09.00	**Arrival**	
09.30	Welcome, Introductions and Overview	P. Morantz
09.45	Individual presentations on Applications for the Meso platform	All
11.00	Grouping and Prioritisation of the most important Applications	All
11.30	Selection of top 3-5 Applications for further investigation	All
12.30	**Lunch**	
13.15	Break-out Group Work: Explore the selected applications	In Groups
14.30	Identify key performance parameters for the application and compare to existing solutions	In Groups
15.30	Identify/Understand the technologies to be developed/integrated	In Groups
16.00	Feedback and Review	All
17.00	**Close**	