Microsystems: A Snapshot of the Present and Future State of the Research Ecosystem

Outputs from the Microscale Systems, Sensors & Devices, and Machines Workshop – May 2022

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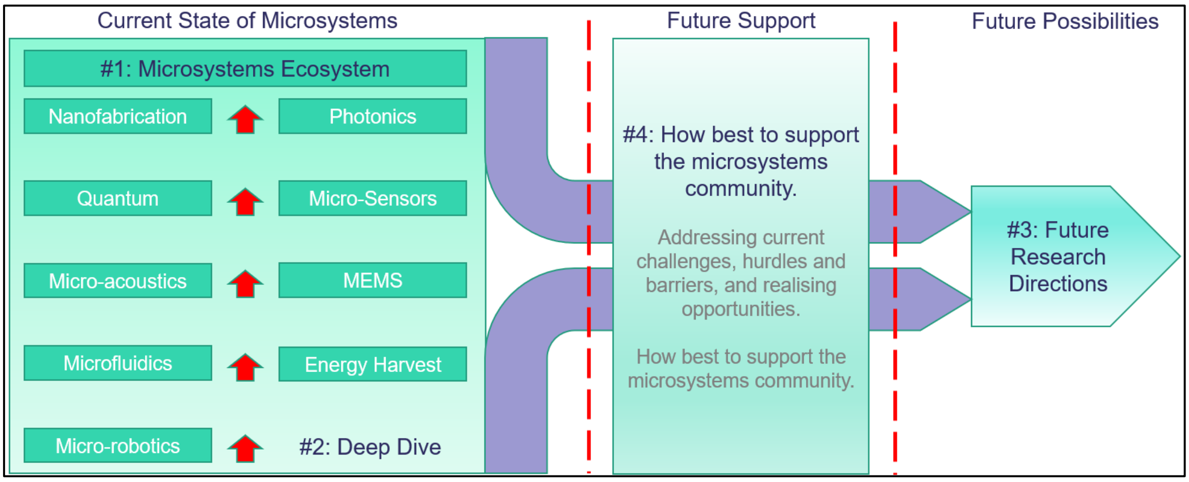
Executive Summary

This report details the outcomes of the *Microscale Systems, Sensors & Devices, and Machines Workshop*. The workshop sought to define the current state of the discipline's research ecosystem, identify future opportunities, and develop a greater understanding of the support needed across the microsystems ecosystem to ensure the area maximises its impact.

The workshop was split into four sessions. Session #1 sought to understand the current challenges facing the wider microsystems ecosystem through a *Strengths, Weaknesses, Opportunities, Threats* (SWOT) analysis. Session #2 then broke down more granularly into the challenges facing eight sub-disciplines of microsystems. Session #3 considered exciting future research directions. And finally, Session #4 brought the previous three sessions together and considered what support could address the identified challenges and realise the potential opportunities. This is summarised in the figure below.



The workshop highlighted the strength and breadth of microsystems research. However, it also highlighted that if the following challenges are not addressed and nothing is done, then the sustainability and capacity of the microsystems researcher pipeline to deliver nationally important and high-quality research, will diminish. Microsystems research would no longer be able to meet UK strategic priorities. These **five cross-cutting challenges** were as follows:

- The **community is highly fragmented** and needs to be brought together to establish new partnerships and collaborations.
- The **researcher and people pipeline** (including cleanroom technicians) **needs to be better supported**.
- **Greater advocacy** is needed for the area, and attendees stressed the need for UKRI EPSRC to ensure that fundamental microsystems research is supported, in addition to application-based research.
- **Better support for systems engineering and improved pathways towards commercialisation** are needed. For example, the quantum-microsystems community could come together to develop standards and undertake requirements capture.
- **Cleanroom facilities are under-supported** and there are pertinent **skills shortages**.

An *Engineering New Quantum Devices Workshop* was also held parallel to the microsystems workshop. The synergies between the two research areas were made apparent, with microsystems being the next iteration of quantum technology as it transitions to more miniaturised products for targeted applications. The challenges with the future of quantum technology closely mirrored the five cross-cutting challenges of microsystems.

Attendees were asked to **paint a picture of a future best-case scenario** for microsystems research, assuming that the cross-cutting challenges are addressed. This vision included:

- Microsystems research groups maintain and advance their **world-leading** positions on the international stage.
- **There is a thriving network** of microsystems researchers that strongly advocate for the discipline across academic and industrial circles.
- There is a **clear sense of community strategy and direction**, with clearly defined goals and grand challenges.
- There is a **strong sense of market-pull from microsystems end-users and industry**, with research pulled through from the low TRLs into industrial applications.
- Training opportunities such as a CDT would help to **maintain the researcher pipeline**, increase cleanroom lab expertise, and lead to new research directions.
- The UK further develops **advanced manufacturing capabilities**, and cleanrooms and fabrication facilities are well supported.

Attendees highlighted that this potential vision for microsystems research could lead to step changes in the technology, as opposed to just incremental. The factors above would ensure that the quality and national importance of UK microsystems research is self-evident to the wider scientific community, and that there is a sustainable capacity of microsystems researchers and programmes to drive forward advances in the technology. Workshop attendees also identified numerous exciting research challenges and opportunities, ranging from improved modelling tools and further miniaturisation down to the nanoscale, through to applications in space and healthcare.

In order to enable the exciting opportunities and realise the best-case scenario vision; the following **key recommendations** were made by the workshop attendees:

1. The community should **establish a network** to enable future collaborations (especially with industry), steer community strategy, and advocate for the discipline.
2. The community should consider routes to **support the researcher and people pipeline** through opportunities such as Centres for Doctoral Training and post-doctoral fellowships.
3. The community should seek to **engage with industry to understand end-user needs** and help translate technology up the technology readiness levels. Examples of mechanisms included sandpits and engaging with professional institutions. UKRI EPSRC are also encouraged to explore strengthening the funding transition to Innovate UK funding.
4. UKRI EPSRC could consider investigating **funding routes for the maintenance of equipment** and facilities, and additional **support for technicians**.
5. UKRI EPSRC could consider running additional **funding calls to support multidisciplinary engineering** and/or targeted **funding calls to support fundamental microsystems** research.

Contents

01 Introduction 5
02 Background 6
02.1 UKRI EPSRC definition of microsystems research: 6
02.2 Where does microsystems sit in the context of UKRI EPSRC? 6
02.3 An analysis of UKRI EPSRC's microsystems portfolio 6
03 Workshop Narrative and Report Structure 9
03.1 Workshop Attendees 10
04 Session #1: What is the current state of microsystems research? 12
04.1 Strengths 12
04.2 Weaknesses 12
04.3 Opportunities 13
04.4 Threats 14
04.5 Feed-Forward from Historic UKRI EPSRC SWOT 14
04.6 Industrial Perspective 15
05 Session #2: Discuss the technical & non-technical challenges for different fields of microsystems research 16
05.1 Common Themes 16
05.2 Summary of Session #2: technical and non-technical challenges for each microsystems sub-discipline 16
06 Session #3: Discuss exciting research challenges, opportunities and future applications. 15
06.1 Three Key Research Challenges 15
06.2 Future Application Areas 16
06.3 Grand Challenges 16
07 Session #4: What opportunities are there for the microsystems ecosystem and researcher pipeline to further supported? 17
07.1 Potential Support Mechanisms 17
07.2 A 5-Year Vision for the Future 22
08: Conclusion 23
Annex 1: Detailed discussion of the technical & non-technical challenges for different fields of microsystems research 25
A.1 Sub-fields 25
A.1.1 Micro/Nanofabrication 25
A.1.2 Quantum 25
A.1.3 Micro-sensors 26
A.1.4 Microfluidic Devices 27
A.1.5 MEMS 28
A.1.6 Micro-acoustic Devices 28
A.1.7 Energy Harvesting Devices 29
A.1.8 Micro-robotics 30
Annex 2: Attendee List 31

01 Introduction

This report follows the *Microscale Systems, Sensors & Devices, and Machines Workshop* held on the 9th May 2022 at The Crowne Plaza Hotel in Manchester. The workshop sought to define the current state of the discipline's research ecosystem, identify future opportunities, and develop a greater understanding of the support needed across the microsystems ecosystem to ensure the area delivers maximum impact.

This report details the outcomes of the workshop and combines them with pre-existing UKRI EPSRC research. The final section details potential future pathways and interventions that the community feels would be of benefit to supporting microsystems research.

The document is intended to capture the current perceptions of the community. UKRI EPSRC acknowledges that this is therefore just one document in an ongoing journey to understand the microsystems community as it continues to evolve and the landscape changes. Recipients of this report are encouraged to engage with UKRI EPSRC going forward when opportunities arise.

02 Background

Microsystems research per-se is a relatively small research area within the UKRI EPSRC portfolio and dominated by applications-driven research with a strong healthcare focus, reflecting the UK's strength in the area. This section further explores microsystems research within the UKRI EPSRC portfolio.

02.1 UKRI EPSRC definition of microsystems research:

Microsystems encompasses a broad spectrum of underpinning micro-engineering research aimed at developing a diverse range of novel miniaturised micro-structured devices, including microfluidic, microelectromechanical, and micro-fabricated devices. Research can be generic in nature or focused on developing devices targeted at a specific end use. Microsystems can be key enabling technologies, with applications in almost every industrial field.

02.2 Where does microsystems sit in the context of UKRI EPSRC?

It is important to recognise how microsystems research aligns to UKRI EPSRC's aims and priorities, and thus, UKRI EPSRC's role in delivering against national priorities and addressing global challenges. To underpin these aims and priorities listed below, UKRI EPSRC must work in partnership with key stakeholders across the research and innovation ecosystem. Microsystems researchers have roles to play in supporting this. Such partnerships with UKRI, government departments and the wider community ensures UKRI EPSRC can:

- **Enable a more equitable, connected and sustainable world-class ecosystem**, to deliver excellent research and innovation, catalyse industry investment across the UK, and facilitate diverse career paths.
- **Lead and underpin UKRI strategic priorities** including in AI, quantum technologies and net zero, to deliver government strategy and resilience to future challenges.
- Attract, upskill and retain the next generation of global research and industry talent, **developing the skills that underpin multidisciplinary research and deliver economic growth** to level up across the UK.

These outcomes address several key government strategies, including the R&D Roadmap, Innovation Strategy, Integrated Review, R&D People and Culture Strategy, Levelling-Up White Paper, and Net Zero Strategy.

As a highly multidisciplinary and underpinning research area, with multiple sectors reliant on microsystems technology, microsystems research has the potential to enable UKRI EPSRC to achieve these aims and priorities. This workshop sought to explore how the microsystems community can support UKRI EPSRC and vice versa. As such, the UKRI EPSRC strategies outlined above were used to develop a framework for evaluating the outputs of the workshop. This was in the form of three key criteria: the *quality, national importance,* and *capacity* of microsystems research. Definitions for these three criteria can be found in Section 03.

02.3 An analysis of UKRI EPSRC's microsystems portfolio

The microsystems field and associated community are diverse, with researchers responding to new challenges, application areas and research directions. However, microsystems research only constitutes a small part of the UKRI EPSRC portfolio, with a total portfolio size of £10.9M (as of 13/06/22) for research and £2.1M for training. Research investments represent 0.31% of the total UKRI EPSRC portfolio; with just £3.1M led by its home theme, engineering. Microsystems research represent just 0.9% of the total engineering portfolio. Investments are across 22 different institutions.

UKRI EPSRC recognises that the microsystems community has a history of strong industrial collaboration and partnership, particularly for applications-driven research; and that fundamental microsystems research, less driven by application, has the potential to increase the underpinning science and engineering knowledge base and have a broad impact across the breadth of microsystems research. Recent years, though, have seen a gradual decline in fundamental microsystems research, as shown by the blue line in Figure 1 below.

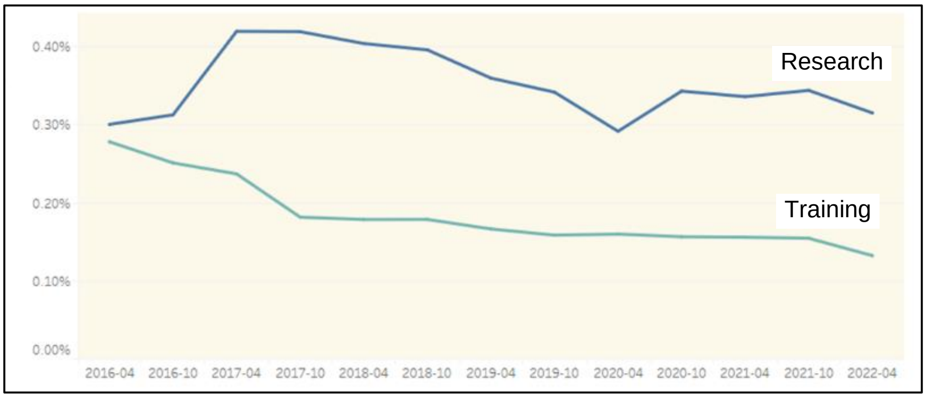


Figure 1: Microsystems research (blue) & training (green) as a % of UKRI EPSRC's portfolio.

To explain this trend, a deeper look into the portfolio and understanding of how UKRI EPSRC classifies grants is required. Grant applications are classified by the percentage relevance of its work-programme to a particular research area. Grants with over 50% relevance to microsystems research are said to have a majority stake, and grants with 10-50% relevance to microsystems are said to have a co-funded minority stake. Within the microsystems portfolio, only 8 grants have a majority stake in microsystems research, and a large proportion of the portfolio (£4M) is attributed to minority stakes of less than 30% in four programme grants. The equivalent value of grants with a majority stake above 50% is just £2.1M; one grant is a fellowship, three are standard research grants, and four are New Investigator Awards (NIAs). The total funding of all community-led standard research grants is just £2.5M (including all grants with 10-100% stakes). The apparent decline in microsystems research appears to be due to a diminished level of community-led grant applications; the equivalent number of grant applications (i.e., adding the percentage relevance to microsystems research on each grant) has averaged at 14 per year, with Engineering Theme success rates at ~25%. Investments in community-led standard mode grants could drop below £2M per year by 2024.

To further explain this trend, the perception of the community is that many microsystems researchers are more likely to align themselves with specific application areas rather than to a broader microsystems community. This has led to a level of community fragmentation. Figure 2 shows that an increasing proportion of microsystems grants have less than a 50% stake – with researchers most commonly aligning to the following research areas: *Sensors and Instrumentation, Fluid Dynamics, Performance and Inspection of Mechanical Structures and Systems, Optoelectronics, Optical Devices and Circuits, Microelectronics, Photonic Materials, Graphene and Carbon Nanotech, Analytical Science, Manufacturing Technologies, Clinical Technologies.* Evidently, microsystems research is indeed "being done"/funded across the UKRI EPSRC portfolio (healthcare, manufacturing, ICT, physical sciences, engineering themes), but is of an applied rather than fundamental nature and is being absorbed into other research areas, reducing the fields' visibility.

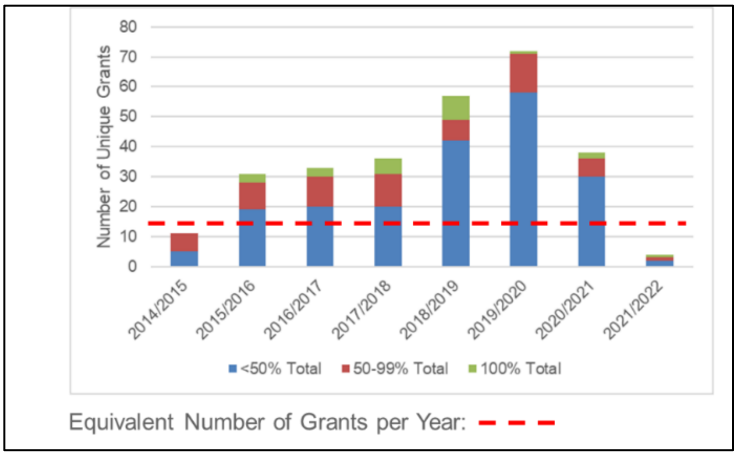


Figure 2: The % relevance to microsystems of unique grants within the portfolio, with time.

Furthermore, it has been reiterated through community engagements that the last decade has seen the portfolio move from basic/fundamental research to more application-driven research. This could be driven by community perceptions of funder policies and peer review priorities.

It was also identified that numbers of UKRI EPSRC first grants (NIAs) remain low, and that there are opportunities to further support the pipeline of future researchers. The green line in Figure 1 indicates that funding for training has been decreasing and that the number of new studentships (green line in Figure 3 below) is also falling. There are no CDTs in the microsystems portfolio. There are concerns that the pipeline of researchers may be unsustainable.

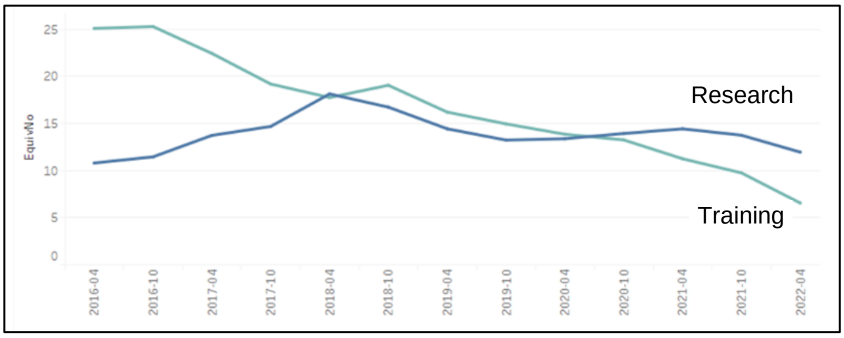


Figure 3: Equivalent number of microsystems grants (blue) and studentships (green).

Finally, it is worth noting that community engagements have indicated that there is no strong sense of a microsystems community; opportunities to establish common interest groups, networks and coordinated community leadership would strengthen the area.

The need for the *Microscale Systems, Sensors & Devices and Machines Workshop* was informed by this portfolio analysis, and through engagement with the microsystems community. There was real emphasis on the need to bring the community together to better understand the trends highlight above and identify future pathways forward. Consequently, a key purpose of the workshop detailed in this report, was to identify and reaffirm the existing challenges/hurdles facing the community, and begin to consider how they might be addressed.

03 Workshop Narrative and Report Structure

The purpose of this workshop was to gather a complete snapshot of the current microsystems research ecosystem, understand future research opportunities; and consequently begin to identify how the hurdles, barriers and challenges might be overcome in order to realise these opportunities. The workshop narrative is summarised in Figure 4: Workshop Narrative.

Session #1 began by looking at the wider-UK landscape and attendees were asked to develop a *Strengths, Weaknesses, Opportunities, Threats* (SWOT) analysis drawing from their lived experiences and expertise of the microsystems area. Session #2 then delved deeper into the individual disciplines within microsystems. Attendees were split into groups based on their expertise and asked to think about the technical and non-technical challenges in their area. Attendees were also asked to think of synergies across the microsystems disciplines and wider-UKRI EPSRC portfolio. These two sessions fed into Session #3. Attendees were asked to discuss exciting future research challenges, opportunities and applications.

The final session, Session #4, then posed the question "what opportunities are there for the microsystems ecosystem and researcher pipeline to be further supported". I.e., how best can UKRI EPSRC, but also the community independent of direct UKRI EPSRC involvement, best support the microsystems community.

In each session, attendees were asked to think about three separate criteria:

- Quality: *The international standing of UK research in microsystems, the transformative or disruptive potential of research in the area and whether the UK's capability in the area is unique in an international context.*
- National Importance: *What is the potential impact of this research area on the current or future success of the UK economy or the development of key emerging industry(s)? Does the area make a clear contribution to meeting key societal challenges facing the UK? Is the area key to the health of other research disciplines?*
- Capacity: *Is there a healthy population and profile of UK researchers of international standing active in the area? Is there appropriate access to facilities and equipment when required? Are there suitable mechanisms for interdisciplinary working?*

The report is written in four sections based on the individual workshop sessions. In each case, comments are related back to these three key criteria, and a concluding section summarises the outputs.

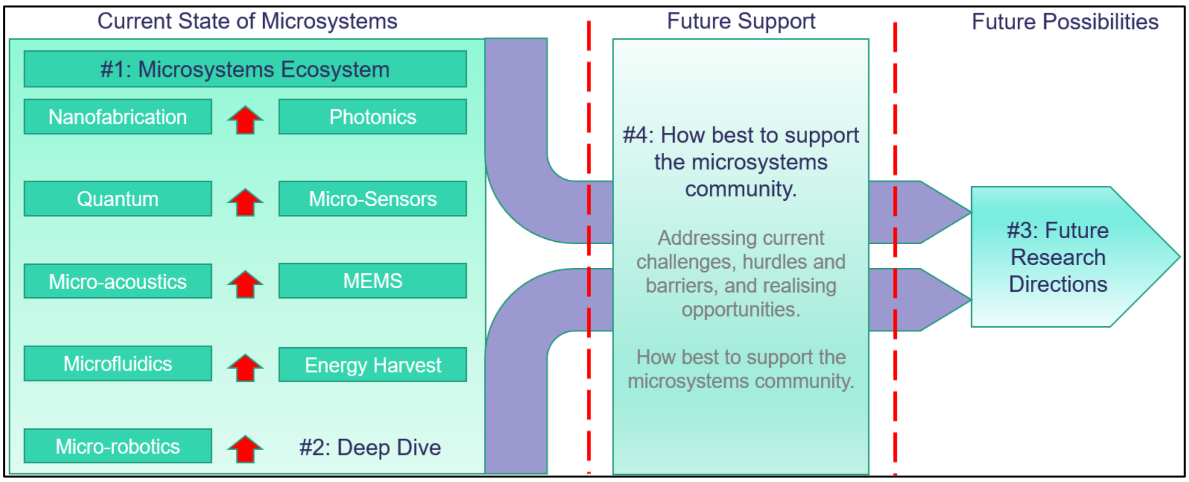


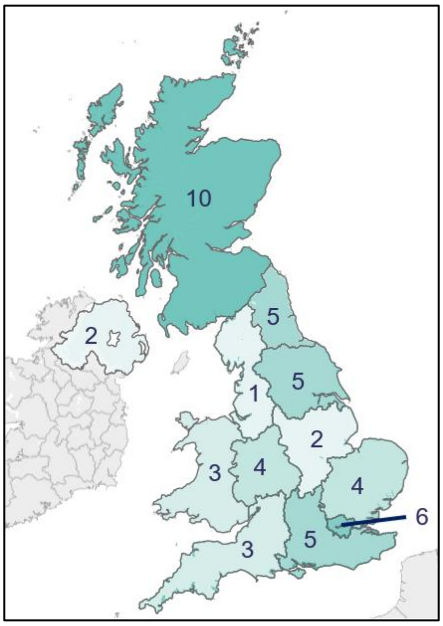
Figure 4: Workshop Narrative

03.1 Workshop Attendees

UKRI EPSRC received over 90 expressions of interest for this event and selected 50 applicants from 30 different institutions to attend. 15 attendees were also invited to the *Engineering New Quantum Devices Workshop* on the 10th May. We encouraged applications from academics of varying career stage and with expertise across the breadth of the field. Colleagues from industry and the third sector were also encouraged to apply, in order to foster relationships between industrial needs and fundamental science research, as well as supporting UKRI EPSRC to ensure non-academic drivers are reflected in future priorities and scoping activities.

Presentations were provided by Dr Ian Sturland (BAE Systems) on *An industrial perspective on Microsystems*, Professor Marc Desmulliez (Heriot-Watt University) on *Putting the "S" back into MEMS*, and Dr Firat Güder on *Microsystems Technologies for the Food Systems*. The presentations proceeded Sessions #1 - #3 respectively and set the scene for each session's discussions.

The following data in Figure 5 also indicates that attendees were from all regions of the UK and highlights the unique strength of microsystems in different groups across various institutions. Additionally, there was a good spread of representatives from industry, early career academics, and established career academics.

a) 

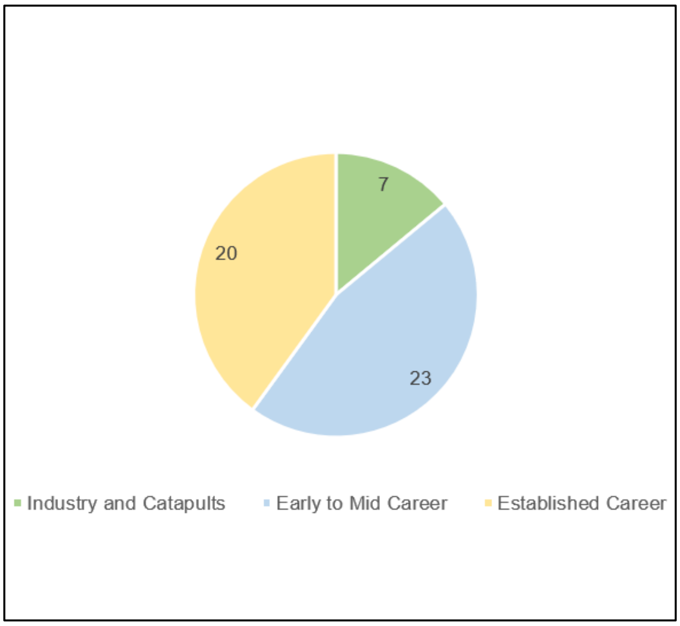
b) 

Figure 5a: Attendees by geographical regional. Figure 5b: Attendees by Career Stage / Type

04 Session #1: What is the current state of microsystems research?

In this session, attendees were asked to develop a SWOT analysis of the current state of microsystems research, bearing in mind the three workshop criteria: *quality*, *national importance*, and *capacity*.

This section provides a brief summary against these three criteria. The list provided is non-exhaustive; only key points are drawn out. The findings are also presented with a historic UKRI EPSRC SWOT analysis, to gauge what might have changed since previous UKRI EPSRC engagement with the community; as well as several additional comments raised by representatives from industry.

04.1 Strengths

Quality of microsystems research:

> *Attendees highlighted that the UK has world-leading groups in centres dotted across the UK and in niche areas of microsystems. Attendees highlighted that UK-based researchers deliver very high-quality research and real innovations in complementary fields and are very good at inventing clever small technology. Several examples were highlighted, these included but are not limited to: energy harvesting, MEMS, lab-on-a-chip and gravity microsystems technology. UK strengths are particularly relevant to research in the Technological Readiness Levels 3-6, i.e., applied research.*

National importance of microsystems research:

> *Attendees stressed the importance of microsystems research as an enabling technology. The community is very diverse, meaning a broad portfolio of underpinning research is across the biomedical, physical sciences, aerospace and manufacturing sectors. The technology is critical to the health of other disciplines and it was highlighted that the next stage of quantum technology development will be dependent on microsystems knowledge. The diversity of the field also enables translational research from one sector to another.*

Capacity of microsystems research:

> *The UK has advanced fabrication facilities dotted across the UK in research organisations including (but not limited to) Glasgow, Southampton and Edinburgh.*

04.2 Weaknesses

Quality of microsystems research:

> *It was highlighted that the UK does not have a presence in high volume microsystems – countries such as the US lead in this regard.*

National importance of microsystems research:

> *Attendees felt that there is not sufficient fundamental research occurring in the microsystems ecosystem. This is in part due to the perception that funding bodies typically only award grants to applied microsystems research. There is still lots of fundamental science within microsystems yet to be explored, so the lack of funding in this area is a weakness.*
>
> *A significant challenge echoed by many attendees was that there is a lack of market pull in the microsystems sector and not enough input from end-users to help drive*

innovation. This issue is compounded upon by a disconnect between academia with the catapults and industry, and also the lack of UK supply chain. The loss of manufacturing capability in the UK and demise of companies' activity in the UK such as with Qinetiq, has negatively impacted research. For instance, the number of collaborations has reduced and there is less guidance from end-users to direct academic research.

Capacity of microsystems research:

Attendees felt that the microsystems community has been highly fragmented for a long-while, meaning that there is no coherent strategy or advocacy for the discipline, and few collaborations between research groups.

Universities are also generally not good at commercialising novel academic technologies – attendees felt this is in part due to universities' inconsistent IP and equity policies.

Attendees highlighted challenges in maintaining/retaining students' interest in hardware development, as microsystems has to compete against artificial intelligence and machine learning research. As such, there is a lack of capacity in student training.

04.3 Opportunities

Quality of microsystems research:

Attendees highlighted that 40% of global electronic design is "fabless"; the UK could position itself to exploit this area and lead internationally. Furthermore, new technologies for fabrication and assembly, and in new materials including semi-conductor and piezo-materials, could be leveraged to invent new microsystems technologies, giving the UK early leads.

A more exhaustive list of important applications and technologies that could have a significant bearing on the quality of UK microsystems research are discussed in Section 06.

National importance of microsystems research:

Microsystems are enabling technologies for several government priorities including Net Zero and sustainability; safeguarding position and navigation technologies (which feature microsystems technology) is also in the national risk register.

A more exhaustive list of important applications and technologies that could have a significant bearing on the national importance of UK microsystems research are discussed in Section 06.

Capacity of microsystems research:

A network in the area could lead to a connected community and more collaborations. This could help the community identify fundamental and grand research challenges. It could also lead to "community mapping", helping to identify companies and SMEs with applications relevant to microsystems, strengthening industrial links to academia.

Microsystems is inherently interdisciplinary, there is the opportunity to attract students from a wide range of disciplines (chemistry, physics, engineering, biology).

The capabilities and opportunities at different fabrication facilities could be signposted, and management centralised. This could lead to the sharing of common technology *and standardisation of processes such as polymer patterning, thin film metallisation etc.*

04.4 Threats

Quality of microsystems research:

Attendees highlighted that world-leading microsystems research is being undertaken in other areas of the UKRI EPSRC portfolio (e.g., quantum), but is not labelled as microsystems research. This reduces the visibility of the area to outside stakeholders, and could lead to further fragmentation, as well as reducing the levels of funding for fundamental research. There is also no centralised view on what microsystems capabilities are, and there is no recognisable core/focus. Attendees were concerned that funders such as the UKRI EPSRC definition of microsystems does not fully encapsulate the range of technology and applications, leading to some research opportunities being missed.

National importance of microsystems research:

Attendees indicated that there is a dependence on overseas technologies and suppliers across the ecosystem.

Capacity of microsystems research:

There is a lack of skills across undergraduate, MSc, PhD, and technicians to build a future microsystems research ecosystem. This has led to a shortage of early career researchers and risks a decline in the number of individuals entering academic positions, threatening the long-term sustainability of the area. There is also a lack of people with systems capability across academia and industry.

A significant issue for the community is the lack of sustained funding and support for laboratory facilities (e.g., cleanrooms), and in some cases there are barriers to accessing these facilities (e.g., cost, geography). Lots of microsystems research is dependent of hardware testing, this issue threatens future research. The UK has a lack of large facility investment compared with the US and China, and there are not currently funding mechanisms to help maintain existing equipment. This could lead to a degradation of facilities, and/or reduced levels of research.

04.5 Feed-Forward from Historic UKRI EPSRC SWOT

In recent years there have been several other engagements with the microsystems community. Many of this workshop's comments confirmed the findings of historic SWOT analyses. Points from the historic SWOTs that are still relevant but were not covered by attendees in detail at the workshop are highlighted below:

- Weakness: It is difficult to describe the area of microsystems – the UKRI EPSRC definition is very broad and includes the use of Microsystems.
- Opportunities: Research in non-silicon microsystems is growing.
- Opportunity/Threat: There is a need to involve other disciplines and explain to younger researchers what the value of microsystems are and what they are capable of.
- Opportunity/Threat: There is a large microsystems research presence outside of the UK in Germany, South Korea and the US, particularly in silicon microsystems. However, the UK can have an impact on the discipline through smart ideas / innovation. For instance, unlike CMOS devices, MEMS research is less reliant on state-of-the-art facilities and this enables much more accessible research.

04.6 Industrial Perspective

During the workshop, Dr Ian Sturland of BAE Systems presented his view of the current state of microsystems research. In addition to the SWOT analysis above, Dr Sturland highlighted that there are some very successful niche-to-mid-volume companies that work in microsystems, and other companies that form an important element of the microsystems supply chain.

These companies include (but may not be limited to):

- Druck
- Semefab
- BAE Systems
- The Technology Partnership
- Inex
- Centronic
- Micro Semiconductor Ltd
- Nexperia
- Plessey
- IXYS
- Sivers Semiconductors
- Diodes Incorporated
- Teledyne
- epigem
- Dolomite
- Lightcast
- Flusso
- Nanusens
- Rockley Photonics
- zeropoint motion
- Cμfab
- soften technologies
- microsaic systems
- IceMOS
- IQE
- Oxford Instruments – Plasma Technology
- SPTS
- Plasma Therm
- Scientific Vacuum Systems Ltd
- G&H
- bay photonics
- Alter Technology
- Silicon Sensing
- Collins Aerospace
- Atlantic Inertial Systems
- Silicon Microgravity
- Owlstone
- Owlstone Medical

Attendees highlighted that further work is needed to map the range of SME's, start-ups, and industrial companies across the UK which have vested interest and capabilities in microsystems technologies.

05 Session #2: Discuss the technical & non-technical challenges for different fields of microsystems research

Session #2 built on Session #1 by asking attendees to identify whether there are any additional, more granular challenges (technical, non-technical) for the different sub-disciplines of microsystems. Nine sub-disciplines were identified. Additionally, attendees were asked to identify whether there are any knowledge gaps in the area, how the area aligns with the *quality, national importance* and *capacity* criteria, and what synergies there are to the other sub-disciplines of microsystems and wider UKRI EPSRC portfolio.

Section 05.2 summarises the findings from the sub-groups relevant to these different areas. Full detail is provided in Annex 1.

NB: micro/nano-photonics was also identified as a sub-discipline, however, there were not enough attendees with the relevant expertise to run a session on this topic.

05.1 Common Themes

The common challenges identified across the eight sub-disciplines listed in Section 05.2 are as follows:

- Challenges with accessing equipment / cleanrooms / labs.
- Challenges with commercialising technological innovations.
- Challenges with standardisation and systems engineering.
- Challenges with advocacy.

These challenges are further addressed in Section 06.

Section 05.2 also indicates just how interdisciplinary the field of microsystems is, with lots of synergies both within the microsystems community, but also to other areas of the UKRI EPSRC portfolio.

05.2 Summary of Session #2: technical and non-technical challenges for each microsystems sub-discipline

For table, see overleaf.

Micro / Nano-fabrication			
Challenges and Knowledge Gaps	Relation to Quality, Importance, Capacity	Synergies	Example UKRI EPSRC Investment
• There is a lack of funding for equipment, especially for maintenance. Fabrication facilities are also decentralised and are often highly customised. Community mapping to highlight different facilities capabilities would be beneficial. • There have been difficulties in academics acquiring project partners, despite industries interest in the area.	The area is embedded in important capabilities in the UK, particularly healthcare and quantum. To maintain the *quality* of research in this area, there needs to be more support for cleanrooms to prevent specialist labs closing. Greater advocacy in this area to highlight its *national importance*, could be beneficial.	• Healthcare technologies • Quantum devices • Photonics	AFM-based nano-machining: developing and validating a novel modelling approach for effective process implementation in nanotechnology applications

Quantum Devices			
Challenges and Knowledge Gaps	Relation to Quality, Importance, Capacity	Synergies	Example UKRI EPSRC Investment
• Technical challenges relate to producing devices with long-term stability, developing better understanding of material properties, and achieving nano-scale precision. • Non-technical challenges include the need to build capability and skills in the verification and validation of quantum devices, and targeting technologies suitable for mid-volume devices.	Quantum is a UK government priority for investment. UK manufacturing capability in the area is of high *national importance*. To sustain the quantum field, programmes of research in adjacent fields, e.g., microsystems, are essential. International research agreements could lead to new quantum collaborations. The UK has good *quality* in the area and is internationally leading in quantum clocks, gravimeters and magnetometers.	• Fundamental physics • Chemistry • Biology / Life Sciences • MEMS • Microsensors	Quantum Imaging for Monitoring of Wellbeing & Disease in Communities

Micro-Sensors			
Challenges and Knowledge Gaps	Relation to Quality, Importance, Capacity	Synergies	Example UKRI EPSRC Investment
• Technical challenges relate to multiplexing of sensor modalities, packaging and material selection.	Ecosystem wide, a *nationally important* non-technical challenge, is the need to improve commercialisation pathways.	• All sub-fields • Nanochemistry	Electrochemical Analyser Microchip with Monolithic

• Embedding sustainability and end-of-life consideration into designs.	This links to embedding standards and systems engineering in research practice.	• Healthcare	integration of Nanoelectrode Array and Instrumentation
Microfluidics			
Challenges and Knowledge Gaps	Relation to Quality, Importance, Capacity	Synergies	Example UKRI EPSRC Investment
• There are a lot of research opportunities around fabrication with PDMS and 3D printing. Additionally, the physics of microfluidics is not well understood and impedes the development of modelling. • Non-technical challenges include difficulties in commercialising technology; this is often affected by non-disclosure agreements. Standardisation of components could help improve this. • Microfluidics is very interdisciplinary; developing the right skills and building lab groups takes a lot of time and effort.	UK has high *quality* in the field and is internationally leading on medical (lab-on-a-chip) devices. Environmental and water quality microfluidics present possible research opportunities. The UK could build *capacity* in these multidisciplinary areas. Fundamental microfluidics research is *nationally important* due to its underpinning nature. Attendees suggested the community should identify grand challenges to direct future research.	• Healthcare technologies • MEMS • Sensors	UKRI EPSRC-SFI: An ocean microlab for autonomous dissolved inorganic carbon depth profile measurement
MEMS			
Challenges and Knowledge Gaps	Relation to Quality, Importance, Capacity	Synergies	Example UKRI EPSRC Investment
• MEMS technologies are a prime example of microsystems that have poor visibility due to the research being absorbed to application-specific areas. There is also the perception that other (non-microsystems researchers) do not appreciate the complexity of MEMS devices. Greater advocacy is needed.	As an underpinning technology key to the heath of many disciplines, MEMS are *nationally important*, especially those with a key design driver being miniaturisation. There are concerns that the UK *capacity* in the area is decreasing as not enough new PhD students are entering the area.	• Quantum devices • Novel materials • See Annex 1 for more detail	MEMS-enabled miniaturised multimodal microscopy through pulsed structured illumination
Micro-Acoustic Devices			

Challenges and Knowledge Gaps	Relation to Quality, Importance, Capacity	Synergies	Example UKRI EPSRC Investment
• Technical challenges include the need to further miniaturise devices, adopt novel acoustic metamaterials, develop phononic band-gap devices and research non-linear behaviour. Micro-acoustics could also be multiplexed with other sensing modalities.	There is a lot of strength and *capacity* in acoustics across the UK and several international companies have been attracted to the UK as a consequence. The *capacity* could be further increased by communicating with other non-acoustic research groups to help develop multiplexed sensing devices.	• Healthcare technologies • Energy harvesting • Metamaterials • NDT	RESINators - Miniature Acoustic Resonator Systems
Energy Harvesting			
Challenges and Knowledge Gaps	Relation to Quality, Importance, Capacity	Synergies	Example UKRI EPSRC Investment
• Because no environment/application is ever the same, developing devices with low achievable power levels is always a technical challenge. Additionally, energy harvesters do not scale well, and the reliability of piezoelectric materials is can undermine device performance. • Awareness of energy harvesting outside the direct community is limited. Greater advocacy for the area is needed.	The UK has high *quality* research in this area and is internationally leading. There are several networks (see Annex for details) which have enabled the UK strength in this area and ensured a sustainable researched pipeline. The driver for sustainable devices may further increase the *national importance* of this area.	• Systems engineering • Electronics • Biomedical devices • Devices for harsh environments	Self-powered wearable sensors for vital signs monitoring
Micro-Robotics			
Challenges and Knowledge Gaps	Relation to Quality, Importance, Capacity	Synergies	Example UKRI EPSRC Investment
• Technical challenges include the integration of devices across various scales, integrating remote power and developing materials reproducible at the microscale.	The UK has developing *quality* internationally leading research in a number of niche robotic applications such as catheters/fibres for surgery. The wider UK communities in electronics, (macro) robotics and sensing, have clear leads	• Bio-inspired design • Healthcare technologies	Wellcome UKRI EPSRC Centre for Surgical and Interventional Sciences

• A key non-technical challenge highlighted was the limited availability of manufacturing and fabrication facilities for research purposes.	internationally that could be capitalised upon to grow the micro-robotics area. Robotics is a *nationally important* priority for the UK government. To open up this potential *capacity*, research silos need breaking and greater engagement across the microsystems community is needed.	• Systems engineering • Devices for harsh environments	

06 Session #3: Discuss exciting research challenges, opportunities and future applications.

Following on from Session #1 and Session #2, attendees were asked to think about exciting future research directions, challenges and opportunities. Attendees were encouraged to think about the research synergies between the different areas and whether there are any topics that could be addressed by the community as a whole.

Attendees were asked to prioritise their ideas based upon the *Importance* and *Quality* criteria listed in Section 03 - i.e., are there any areas that could lead to the UK having a unique capability internationally; and what challenges if resolved could deliver impactful research (both in terms of wider societal impact, as well as fundamental research impacts on different fields). Figure 6 demonstrates the diverse list of exciting research directions that attendees identified. As attendees commented, this indicates both a strength and weakness of the microsystems community – it is highly diverse and has impacts across a wide range of fields and sectors, but also in turn means it is also difficult to converge around and prioritise single arguments.

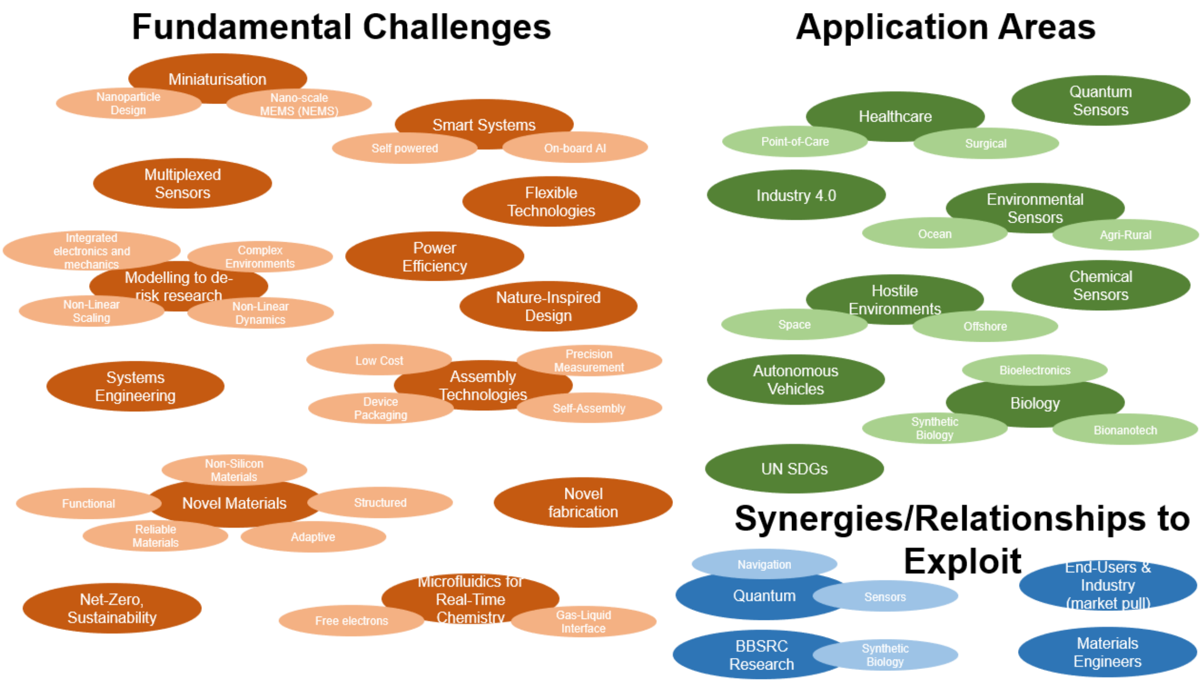


Figure 6: A summary of the key exciting research directions attendees identified.

That being said, three key research challenges were identified; the remaining comments are separated into research challenges, research applications and important synergies with other research areas that could be better exploited.

06.1 Three Key Research Challenges

1. The most widely recognised research challenge attendees identified was improvements in systems engineering practices/research. Systems engineering involves solving questions such as designing for integration, designing to build in redundancy, and modelling non-linearities to better understand critical interfaces and component behaviours. Two key examples were highlighted: systems engineering for quantum-microsystems, which involves the development of standards and standardised requirements for the technology; whole systems approaches to healthcare, ensuring the appropriate engagement with end-users, regulatory bodies

and multidisciplinary research teams to ensure appropriate methodologies are devised at project inception.

2. The continued need to miniaturise devices across a broad range of applications and sub-disciplines. This represents a key constituent aspect of fundamental research that microsystems researchers need to continue exploring and is an especially pertinent challenge for quantum technologies. Several attendees also raised the idea of incorporating Nano-MEMS or NEMS into the UKRI EPSRC definition of microsystems.
3. There are a whole host of new materials being developed all the time: functional, structural, adaptive, sustainable, and non-silicon. There is fundamental research in understanding and characterising these materials for microsystems applications, for instance, understanding how reliable these materials are for micro-packaging and energy harvesting.

Other challenges included: developing CAD design tools to help model complex environments (e.g., blood), non-linear dynamics, and systems that do not scale linearly; develop new fabrication methods, creating smart systems, developing nature-inspired devices, low-cost and self-assembled devices, increasing the precision of device actuation and measurement, and finally developing devices for Net-Zero / Sustainability (e.g., end of life considerations).

06.2 Future Application Areas

The application areas presented in Figure 6 were identified as sectors which can contribute to elevating the national importance and quality of microsystems; i.e., further help the community to develop an internationally leading niche.

These application areas require exploiting research synergies and building connections with:

- The quantum community.
- The BBSRC research community (e.g. synthetic biologists).
- Materials engineers.
- End-users / Industry to help microsystems academics better define end-user problems and help create a market pull as well as a technology push.

06.3 Grand Challenges

Whilst it is widely acknowledged that the microsystems community is almost too diverse for it to group behind a single application area or challenge, the following applications represent problems large constituent elements of the microsystems community could seek to address:

- Grand challenges in creating sustainable water and food supplies.
- Grand challenges in medical devices for an ageing society.
- Grand challenges in realising net-zero.
- Grand challenges in technology for advanced manufacturing.
- Creating micro-robots as a means to bring multidisciplinary groups together.
- Developing modelling and software for microsystems to help de-risk projects and unlock commercialisation. I.e., create models that integrate electronics, mechanical devices and extreme environments.

07 Session #4: What opportunities are there for the microsystems ecosystem and researcher pipeline to further supported?

The outputs of Session #4 were a culmination of the findings from the first three workshop sessions. The aim of the session was to think of approaches both UKRI EPSRC and the community could take, in order to address the current challenges, hurdles and barriers facing the community (Session #1 and Session #2), and also help realise those exciting future research opportunities and application areas described in Session #3.

The session asked attendees to prioritise ideas that would have the maximum impact; but also to be mindful that we (as a research ecosystem) are operating in a resource constrained environment. Attendees were therefore also asked to think about potential avenues of support that could be community-led without direct UKRI EPSRC funding.

Key questions posed in this session included:

- What do you see as the highest priority community needs and opportunities, and how might these be achieved?
- How do we ensure a future researcher pipeline that is diverse and inclusive?
- What UKRI EPSRC-agnostic interventions would the community most benefit from?
- In a resource constrained environment what potential support could UKRI EPSRC offer that would maximise the impact of microsystems research (beyond direct funding opportunities)?
- In five years time what would be the best and worst case scenarios for microsystems if a) nothing is done and b) the proposed solution is implemented?

Attendees were again asked to think about how their ideas relate to the *quality, national importance* and *capacity* of microsystems research (see Section 03 for definitions).

07.1 Potential Support Mechanisms

Eight scenarios and ideas were identified by attendees. This section summarises each idea, the impact it is trying to achieve, and the relative priority afforded to it by the attendees.

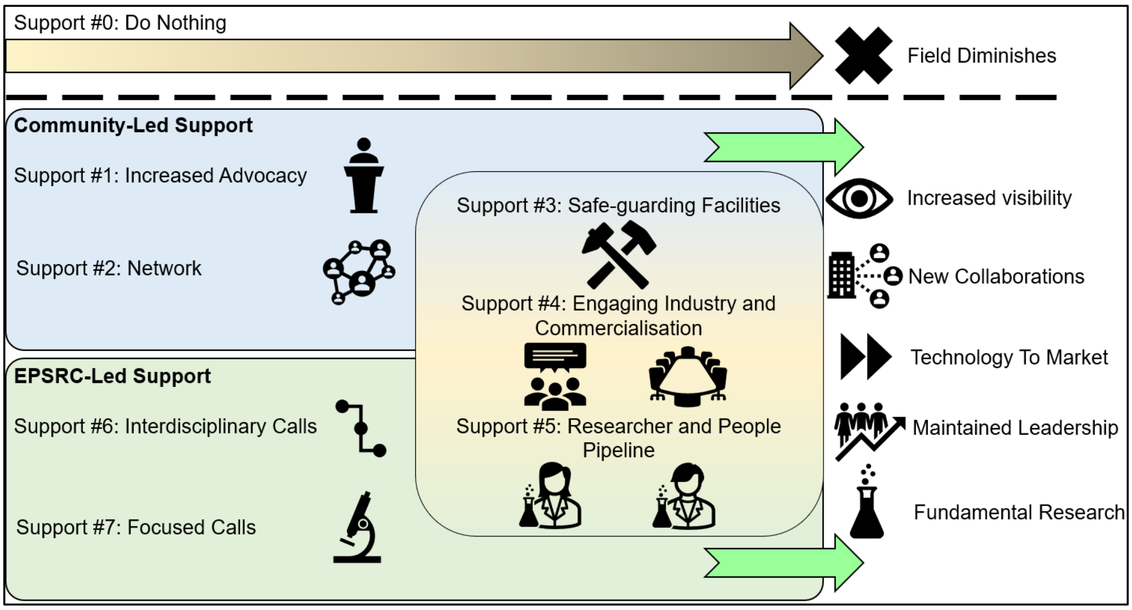


Figure 7: Potential support mechanisms identified by attendees, and their impacts.

Support #0: Do Nothing [Worst-Case Outcome]

Summary: If there is no intervention led by either funders such as UKRI EPSRC or the community then it is likely that the microsystems field in the UK will diminish. This is because recruitment of new early career researchers and PhD students will remain low, and existing UK leaders will retire or move outside of the UK. The people pipeline will become unsustainable.

Impact: UK loses international lead and UK-led microsystems technologies are no longer able to meet UK strategic priorities. Expertise and technology related to Internet of Things and ubiquitous computing have to be imported from overseas.

The *quality*, *national importance* and *capacity* of UK microsystems research are all diminished.

Support #1: Increased Advocacy [Medium Priority]

Summary: The community needs leadership and advocacy to increase the wider scientific community's awareness of the value microsystems research can bring as an underpinning technology that has impact across a diverse range of applications. Attendees highlighted that there have been numerous commercialisation success stories, however, these are not well reported on. There was also the perception amongst attendees that the wider community believe that most microsystems problems have already been solved – as such, the research area is seen as less "attractive", and it is incorrectly perceived that there is no more fundamental research remaining.

Impact: Through greater advocacy microsystems researchers will be able to inspire future talent. There is a strong need to recruit more individuals with cleanroom expertise and advocacy represents a good opportunity to showcase exciting hardware research. Greater advocacy can also help address the wider misconceptions about microsystems research, and through liaising with non-traditional partners (i.e., scientists and engineers with few previous collaborations with microsystems) new application areas might be identified and might help refresh fundamental microsystems research thinking.

The *capacity* of microsystems research will be improved through inspiring future talent to enter the field. The *quality* of microsystems research will improve through new collaborations with non-traditional partners leading to disruptive research, and the *national importance* of microsystems research will be more visible.

Support #2: Network [Highest Priority]

Summary: Prior to and during the workshop, attendees highlighted the need to bring the community together. The community is currently highly fragmented, there is no focal point of leadership and as such there are missed opportunities in developing the research and maximising the impact of the research area. A network would help solve some of these issues and help drive a coordinated strategy for UK researchers.

Impact: Attendees felt that a network would have the greatest positive impact for the microsystems community. Attendees suggested that a network could have the following impacts:

- A network could help microsystems researchers develop a technology roadmap and use as a tool to connect academics and industry together, and align research priorities. This could further lead to the development and identification of requirements and standards, and consequently lead to greater commercialisation opportunities – thereby having a positive impact on the *national importance* of microsystems in contributing to the future success of the UK economy.
- A network could facilitate collaborations, and therefore lead to the development of multidisciplinary programme grants (in for example quantum MEMS). Attendees reflected that programme grants are great for systems and integration research (addressing Session #3's outputs) and enable blue-sky thinking. In doing so, a network would therefore improve the *quality* and international standing of microsystems research.
- A network could fund seed projects enabling basic technologies to be explored.
- A network could help identify grand challenges and future priorities and advocate for the *national importance* of microsystems research.
- A network could help build a case for training supports, such as a Centre for Doctoral Training (CDT) in microsystems, enabling the researcher pipeline of microsystems experts to be better supported and ensuring a sustainable UK *capacity* for microsystems research.

Support #3: Safe-guarding Facilities [High priority]

Summary: Throughout the workshop the lack of funding for the maintenance of equipment and fabrication facilities was raised, in addition to the fact that retention, recruitment and training of individuals with cleanroom expertise is not sufficient. Attendees proposed that it would be useful to connect and network the fabrication facilities together, such that there was increased awareness and access to different facilities capabilities. Alternatively, a mid-range national facility was proposed, however, as identified in Session #2– this may come with difficulties in customisation. Funding for maintenance would also be beneficial.

Impact: It was felt that fabrication and cleanroom facilities are key to the *capacity* of microsystems research as hardware prototyping and testing is a fundamental element of the field. Funding and connecting these facilities together would significantly increase access and in doing so, could enable more fundamental blue skies research; contributing to the *quality* of microsystems research.

Support #4: Engaging Industry and Commercialisation [High priority]

Summary: Attendees highlighted the importance of engaging with end-users and industry to bring them into low TRL microsystems research. At the moment, attendees felt that there is not enough market pull in the UK and in-part, this may be due to a disconnect between industry and academia. Attendees encouraged the idea of opportunities to foster industry-academia collaboration and suggested a mapping exercise could be undertaken to identify large industrial companies and Small Medium

Enterprises (SMEs) around the UK. Attendees also mentioned that engagement with regulatory and standards bodies could lead to better standardisation of the interfaces and design of elements of microsystems.

Attendees felt that there were opportunities to further strengthen translation of research from TRL 3/4 to TRL 5/6 and would like for UKRI and the wider community to consider where this might be possible. Attendees also encouraged further exploration of IP ownership for spin-out companies, suggesting that greater innovation could be stimulated if researchers own the IP generated from their funded research.

Finally, attendees highlighted that the catapults (such as CPI) have their own funding mechanisms and work with SMEs, and encouraged that the wider community to further engage with the catapults.

Impact: Greater industrial collaboration, standardisation and inter-connectedness between UKRI EPSRC-Innovate UK could lead to more avenues for the commercialisation of microsystems research. This could lead to the *national importance* of microsystems research increasing, by enabling the development of new emerging industries. It was strongly emphasised that there is a need for a market pull to be developed and this needs industry and end-users to really specify the challenges they face. Greater IP and equity empowerment for researchers could also lead to increased numbers of SMEs and start-ups.

Support #5: Researcher and People Pipeline [2nd Highest Priority]

Summary: As highlighted in Section 02.3, the number of new microsystems studentships is decreasing. There is also the concern that early career researchers are not “attracted” to the complexity of microsystems research and/or are pulled away to the software fields of machine learning and artificial intelligence. As such, without an intervention to reinvigorate the researcher pipeline, there is a high risk that the level of expertise in the UK will diminish as existing leaders retire. Attendees therefore proposed that the community should seek to understand the reasons why Master’s course in microsystems are not so popular; inspire future female leaders to enter the field; engage in further activities to promote equality, diversity and inclusivity values; and potentially consider further training opportunities, such as a CDT. Several attendees also floated the idea of post-doctoral fellowships to promote the next generation of leaders.

Impact: Doctoral training and fellowships in particular were repeatedly mentioned throughout the workshop, and were strongly believed to be the best way to support the researcher pipeline through to both academia and industry. Training opportunities such as a CDT could promote systems thinking and increase training within cleanroom facilities, addressing the highlighted skills gaps. A post-doctoral fellowship would also encourage more PhD students along a career path in microsystems. This solution does require enthusiastic and impartial community leaders to lead the change. The potential to improve the *capacity* of microsystems researchers in the UK was raised by attendees.

Support #6: Interdisciplinary Calls [Medium Priority]

Summary: Attendees highlighted that UKRI EPSRC's New Horizon's call and the UKRI call in Basic Technologies in Sensors and Imaging were well received by the community. These calls enabled high risk, high reward research, and in the case of the latter enabled truly interdisciplinary research. Yet, there was the perception amongst attendees that there are still opportunities to strengthen peer review processes for interdisciplinary proposals.

Impact: Interdisciplinary calls were seen as a mechanism well suited to microsystems research which is inherently multidisciplinary. Attendees questioned whether there is an opportunity for funders such as UKRI EPSRC to run further interdisciplinary panels. This could help improve the *capacity* for microsystems researchers to engage in multidisciplinary applications.

Support #7: Focused Calls [Medium Priority]

Summary: In light of the low application numbers to UKRI EPSRC highlighted in Section 02.3, workshop attendees proposed that a call in microsystems could help contribute to the sustainability of the field. It was strongly felt by attendees that a funding opportunity for fundamental microsystems research is preferable to an application-orientated call; though there was not an overall consensus on this matter. It was also felt that seed funding, or blind review processes such as those adopted in New Horizon's, would better encourage ECRs to enter the field.

Impact: A dedicated funding call would help develop the *quality* of microsystems research, by helping to develop unique capabilities in the UK. If a seed funding approach was adopted, then there is also the opportunity to develop the *capacity* of ECRs in the UK. As an underpinning technology, fundamental research is critical to the health of other disciplines – a call would bolster the *national importance* of the area.

07.2 A 5-Year Vision for the Future

Through the seven different support mechanisms highlighted above, the workshop attendees were able to develop a vision for what the best-case scenario for microsystems research will look like in the future. Singular or different combinations of support can all have an impact, and the community strongly indicated that there needs to be an intervention that is either community or funder led, or both.

Taking all this in mind, attendees suggested that the best-case future scenario in five years time for microsystems research included the following ideas and vision:

- Microsystems research groups maintain and advance their world-leading positions on the international stage. There is strong evidence of collaboration between different labs and research groups.
- There is a thriving network of microsystems researchers that strongly advocate for the discipline across academic and industrial circles, and promotes the discipline to future generations of engineers and researchers. There is a clear sense of community strategy and direction, with clearly defined goals and grand challenges.
- Through these networks and collaborations, the field has been able to initiate a strong sense of market-pull from microsystems end-users and industry, with research pulled

through from the low TRLs into industrial applications. The community has developed strong links with industry, is able to respond to industry-driven challenges, and maintains regular communication through events such as research showcases and conferences.
- Training opportunities in the area and helps to maintain the researcher pipeline, increase cleanroom lab expertise, and lead to new research directions.
- The UK further develops advanced manufacturing capabilities, and cleanrooms and fabrication facilities are well supported.

All of these factors lead to step changes in microsystems research, as opposed to just incremental. The *quality* and *national importance* of microsystems is self-evident to the wider scientific community, and the microsystems ecosystem has a sustainable *capacity* to drive forward advances in the technology.

08: Conclusion

This workshop sought to identify key challenges facing the microsystems community, exciting future research opportunities, and asked attendees to think about potential avenues of support both funders such as UKRI EPSRC and the community should consider to maximise the *quality, national importance* and *capacity* of microsystems research in the UK.

The workshop highlighted the breadth and talent of microsystems researchers; a core strength of the microsystems community that enables the UK to have some world leading capabilities and ability to address numerous global challenges and future opportunities. Yet, attendees indicated that the UK's strength and *capacity* of talented researchers is under threat. If nothing is done to support the microsystems community then there is a significant likelihood that numbers of researchers in the field will diminish, reducing the *quality* and *national importance* of microsystems research in the UK. The UK will no longer be world leading, and the transformative impacts of microsystems research will not be realised. This is a significant concern for the community given the nature of microsystems research an as underpinning technology key to the health of a vast array of disciplines across healthcare, navigation, and non-destructive testing (to name a few).

It is therefore critical that the following challenges identified during the four workshop sessions, are addressed:

- The community is highly fragmented and needs to be brought together to establish new partnerships and collaborations.
- The researcher and people pipeline (including cleanroom technicians) needs to be better supported.
- Greater advocacy is needed for the area, and attendees stressed the need for funders such as UKRI EPSRC to ensure that fundamental microsystems research is supported, in addition to application-based research.
- There are opportunities to better support systems engineering and consider improved pathways towards commercialisation.
- Cleanrooms and facilities are under-supported and there are pertinent skills shortages.

Both funders and the microsystems community need to reflect on these five key challenges, and identify means in which support can be developed to ensure they are addressed. In doing so, new partnerships, collaborations and mechanisms will help unlock future UK capability and ensure microsystems research is of a high *quality*, is of high *national importance*, and is supported by a strong *capacity* of researchers and programmes.

The workshop was also undertaken in tandem with an *Engineering New Quantum Devices Workshop.* This workshop again reiterated the importance of microsystems as the next iteration of quantum technologies as they seek to become miniaturised devices with application in real world products. There were several cross-cutting themes that parallel that of the microsystems workshop; particularly with regards to the need for improved networking, the need to better support cleanroom facilities and their staff, and the need to adopt systems engineering into the mainstream research culture to help improve pathways to commercialisation.

Finally, UKRI EPSRC would like to thank all attendees of the workshop for making this report possible. UKRI EPSRC acknowledges that this report is just a snapshot of the microsystems ecosystem at the point in time at which the workshop was held. This document is therefore part of a live body of work to engage with and understand the microsystems community. It forms the basis of ongoing UKRI EPSRC strategy in the area. We highly encourage recipients of this report to engage with the relevant portfolio manager(s) in future engagement opportunities.

Annex 1: Detailed discussion of the technical & non-technical challenges for different fields of microsystems research

Session #2 built on Session #1 by asking attendees to identify whether there are any additional, more granular challenges (technical, non-technical) for the different sub-disciplines of microsystems. Additionally, attendees were asked to identify whether there are any knowledge gaps in the area, how the area aligns with the *quality, national importance* and *capacity* criteria, and what synergies there are to the other sub-disciplines of microsystems.

This Annex summarises the findings from the sub-groups relevant to these different areas.

A.1 Sub-fields

Nine sub-fields were identified and are set out below. Note: micro/nano-photonics was also identified as a sub-discipline, however, there were not enough attendees with the relevant expertise to run a session on this topic.

A.1.1 Micro/Nanofabrication

Summary: Attendees highlighted that a fundamental element of microsystems research is being able to prototype hardware in cleanrooms/labs. Not only this, but there is a core UK strength in developing advanced micro/nano-fabrication techniques relevant to microsystems.

Challenges and Knowledge Gaps: The key challenge identified for this area was a lack of funding for equipment, especially for maintenance. This is both from funding bodies and universities. Micro/Nano-fabrication facilities are also currently decentralised, and it is uncommon for all the necessary fabrication capabilities to contained at a single research organisation – this is because equipment is frequently customised for unique applications. Whilst there were multiple comments related to forming a central facility, the focus group suggested that a network highlighting the capabilities of different organisations might be a more appropriate mechanism. This is because centralised facilities are less “customisable”.

It was identified that industry needs/wants more fundamental research in the area, but there have historically been difficulties for academics acquiring project partners.

Relation to Quality, National Importance and Capacity: The area is embedded in important capabilities in the UK, particularly healthcare and quantum. In order to maintain the quality of research in this area, there needs to be more support for cleanrooms, and this is reliant on better advocacy of the importance for micro/nano-fabrication facilities to stakeholders and policy makers. There are concerns that without support, specialist labs may stop functioning.

Synergies: Micro/nano-fabrication has strong synergies with healthcare technologies, quantum devices and photonics.

Example of UKRI EPSRC Investment: AFM-based nano-machining: developing and validating a novel modelling approach for effective process implementation in nanotechnology applications

A.1.2 Quantum

Summary: Throughout the workshop quantum technologies were highlighted as a future avenue for microsystems research. Existing quantum sensors and devices need to be miniaturised, and expertise from the microsystems community can make this possible.

Challenges and Knowledge Gaps: From a technical perspective, challenges identified related to the scaling of devices (particularly cold atom), producing devices with long-term stability, and the need for the microsystems community to better understand quantum scale material properties, characterisation and how plasma fabrication methods might be used to achieve nanoscale precision. A specific application mentioned was ultra-high voltage MEMS with atomic cells for cold atoms and ions.

Other non-technical challenges included overcoming skills gaps, particularly around verification/validation and modelling; but also working to develop devices that are low-mid volume, not just high volume applications.

Relation to Quality, National Importance and Capacity: Quantum is a UK government priority for investment and bringing the community together. The UK manufacturing capability in quantum is also of high national importance. It was highlighted that in order to sustain the quantum field, adjacent programmes in areas such as microsystems are essential. This is especially pertinent as position, navigation and timing in Global Navigation Satellite Systems (GNSS) denied environments is on the national risk register. The UK is internationally leading in quantum clocks, gravimeters, accelerometers, and magnetometers; and international research agreements with the UK in quantum poses both an opportunity and risk to the community as it continues to grow.

That being said, the capacity and ability to continue growing the field is limited by a shortage of suitably qualified expert personnel globally and not having an established supply chain. The community could also better embrace requirements and technology selection methodologies.

Synergies: Links to fundamental physics, MEMS, microsensors, chemistry and biology were identified.

Example of UKRI EPSRC Investment: Quantum Imaging for Monitoring of Wellbeing & Disease in Communities

A.1.3 Micro-sensors

Summary: The largest overlap of the microsystems portfolio with any other UKRI EPSRC research area is with sensors. Microsystems sensors encompass a range of technologies (e.g., photonics, electromagnetic, acoustic) and applications (e.g., biomedical, gravimeter). All bar one attendee at the workshop had expertise in this area.

Challenges and Knowledge Gaps: The key challenges highlighted by attendees were the need for multiplexing of sensing modalities, systems-level integration of devices with other sub-systems, packaging devices, and identifying the best material (silicon and non-silicon) for an application. For specific applications, greater consideration of sustainability is needed (i.e., degradability, end-of-life design). Attendees also highlighted the need for greater collaboration with MHRA for medical regulatory compliance of devices.

The most significant non-technical challenges were related to networking and ensuring sensors technologies have the prospect of being commercialised. Networking is essential for this sub-discipline due to its inherently multidisciplinary nature. Commercialisation requires building greater connections with industry to better inform on end-user requirements. This also closely ties to the need for more systems-engineering, modelling and verification/validation.

Relation to Quality, National Importance and Capacity: There were several comments arguing for the need to create a set of standards (performance definition, critical parameters, methods for validation) for the areas of MEMS and microsensors to really unlock the area and accelerate pathways towards commercialisation. Nationally important application areas include sensors for food (in stores and agrifood) and healthcare.

Synergies: There are strong synergies with all microsystems fields. Nano-chemistry could be a fruitful area for research.

Example of UKRI EPSRC Investment: Electrochemical Analyser Microchip with Monolithic integration of Nanoelectrode Array and Instrumentation

A.1.4 Microfluidic Devices

Summary: Microfluidic devices underpin a broad range of medical and analytical chemistry devices. Research in this area is often very multidisciplinary. A large proportion of attendees (36%) indicated expertise in microfluidics, highlighting the strong UK presence in the area.

Challenges and Knowledge Gaps: A non-technical challenge that has a significant technical bearing, is the lack of polymer etching bonding equipment in the UK. There are also a lot of research opportunities around fabrication with PDMS and 3D printing (i.e., alternatives to soft lithography). There is also a significant research gap in that the physics behind microfluidics is still not well understood, which in-turn means that there are limited opportunities to undertake computer modelling (which could help de-risk research projects).

Attendees were surprised by how few commercial microfluidic companies there are in the UK, indicating another possible challenge with commercialising complex integrated microfluidic devices. This is compounded on by a number of non-disclosure agreements around the specific capabilities for engineering surfaces. Several attendees suggested standardisation could help unlock commercialisation opportunities.

There is also the perception that multidisciplinary research is not well supported by funding bodies. Additionally, multiple lab groups are often required to ensure the correct balance of skills, which takes a lot of time and administrative effort to set up.

Relation to Quality, National Importance and Capacity: The UK has internationally leading research in microfluidic devices for medical applications (e.g., lab-on-a-chip); the majority of funding for microfluidic research going in this direction. However, given the recent Covid-19 pandemic, a significant opportunity was missed by the microsystems community to be involved in developing micro-PCR tests. Going forward there are opportunities in microfluidic devices for environmental and water quality research, and digitalising devices.

There is also still a need for fundamental microfluidics research, which can have a broad impact due to the underpinning nature of the technology. However, there was also the perception amongst attendees that the UK community in microsystems has been too risk adverse. To drive forward fundamental research in the area, greater advocacy for microfluidics is required and grand challenges need to be identified; this will help enable researchers to be braver and push the boundaries of fundamental research.

Synergies: Primarily with healthcare tech, but also across MEMS, sensors, electronics.

Example of UKRI EPSRC Investment: UKRI EPSRC-SFI: An ocean microlab for autonomous dissolved inorganic carbon depth profile measurement

A.1.5 MEMS

Summary: Microelectromechanical Systems or MEMS encompasses a huge variety of devices and 58% of attendees highlighted that they had expertise in this field.

Challenges and Knowledge Gaps: Underpinning MEMS technologies are a prime example of research that has low visibility due to it being absorbed into research grants with specific application areas, or because research groups do not tend to be explicitly MEMS-orientated. There is also the perception that other researchers do not appreciate the complexity and interdisciplinarity of MEMS devices and the challenges in selecting materials appropriate to a devices function. It was highlighted that greater advocacy in this area is required.

Another challenge is that because MEMS typically involve moving structures and require prototyping to validate designs, specific equipment is required that is not readily available – the area is intrinsically dependent on training technicians and students to run cleanrooms, and such equipment.

Specific technical challenges highlighted were the need to produce stable MEMS devices for quantum applications, utilising new materials, developing new simulation approaches, and modelling across a range of direct voltage magnitudes (from mV to KV). Knowledge gaps include micro and non-continuum mechanics, systems integration, and computational skills for developing CAD tools capable of modelling non-linear scale dependencies.

Relation to Quality, National Importance and Capacity: Attendees highlighted that MEMS is an underpinning technology (see synergies below) and key to the health of many disciplines, especially those with a key design driver being miniaturisation. The UK is in the top 7 in the world for number of publications in the area particularly in BioMEMS, but is a big step behind China and the US. Journal publications also tend to be in low impact journals. International research agreements in quantum could help grow the area.

There were concerns that the nature of research is transitioning predominantly to application orientated research, that not enough PhD students are coming into the area.

Synergies: Synergies identified included quantum technologies, nano-chemistry and materials research, novel material development (SiC, GaN, Ga_2O_3, diamond), engineering biology, photonics, energy efficient computing. Applications include clinical tech, automotive, healthcare etc. In essence, MEMS are a platform technology cutting across many UKRI EPSRC themes.

Example of UKRI EPSRC Investment: MEMS-enabled miniaturised multimodal microscopy through pulsed structured illumination

A.1.6 Micro-acoustic Devices

Summary: Micro-acoustic devices have a broad range of applications from micro-loudspeakers, through to surgical instruments. The UK has a number of internationally leading groups in the area, and there is a significant community in Scotland.

Challenges and Knowledge Gaps: Scientific challenges included further miniaturisation of devices, power management, integrating data transfer into devices, adopting acoustic metamaterials, developing photonic band-gap devices, and undertaking research in non-linear micro-acoustic behaviour. A knowledge gap identified was creating devices that multiplex with other sensing modalities.

Relation to Quality, National Importance and Capacity: There is a lot of strength in acoustics more generally across the UK and several international companies have been attracted to the UK as a consequence. The main challenge limiting the capacity of microsystems research in this area is lack of communication between research groups which is essential in the drive to developed multiplexed sensing devices.

Synergies: Strong scientific synergies included in healthcare (particularly acoustic imaging and developing portable devices), energy harvesting, and metamaterial technologies. Application areas include non-destructive testing / structural health monitoring, healthcare, defence (next-generation communications).

Example of UKRI EPSRC Investment: RESINators - Miniature Acoustic Resonator Systems

A.1.7 Energy Harvesting Devices

Summary: Energy harvesting devices has been a researcher area with multiple "homes" within UKRI EPSRC over the last few years including "electronic devices and subsystems" (which no longer exists) and "performance and inspection of mechanical structures and systems (PIMSS)". There is already a network in this area (http://eh-network.org/members.php), and there are strong links to the microsystems portfolio.

Challenges and Knowledge Gaps: Attendees identified that because no environment and application is ever the same, developing devices with low achievable power levels is always a technical challenge. This is especially pertinent with energy harvesting, as systems do not scale well and the reliability of piezoelectric materials can cause problems.

Another key challenge is in terms of advocacy; awareness outside of the energy harvesting community is somewhat limited. Advocacy has been further hindered by there only being a few examples of long-term reliable products that have come out of research. Greater promotion of these successful stories is required.

A final challenge is that the broad application area of this technology makes choosing UKRI EPSRC panels difficult – UKRI EPSRC offers a remit enquiries email box for this purpose (UKRI EPSRC_remit_queries@prep.ukri.org) and it is advised applicants submit through this route if they are unsure which portfolio and/or panel is most appropriate.

Relation to Quality, National Importance and Capacity: The UK is internationally leading in microenergy harvesting. In addition to the Energy Harvesting Network (link above), there is also the Power MEMS network. The networks have really enabled the UK strength in this area and as such, there is a good pipeline of early career researchers and skills base. The greater drive for sustainability could further increase opportunities (i.e., removes the need for batteries).

Synergies: There are strong synergies to system design, particularly those with electronics (mixed mode, high voltage, on-chip magnetics). There are also increasing opportunities in biological and biomedical applications and the advent of single crystal piezoelectric materials represents an exciting research avenue. Future applications include devices for food packaging, logistics, environmental monitoring, smart homes, and devices deployed long-term in harsh environments. New materials and research in dynamics could open up future research in this field.

Example of UKRI EPSRC Investment: Self-powered wearable sensors for vital signs monitoring

A.1.8 Micro-robotics

Summary: Micro-robotics is a growing sub-discipline in microsystems and has strong links to the wider robotics community. Applications typically tend to be of a healthcare nature.

Challenges and Knowledge Gaps: Technical scientific challenges identified included the integration of devices across a range of scales, integrating remote power and sensors into devices, taking inspiration from nature for sensors and actuation, developing computationally efficient algorithms, and developing materials that are reproducible at the microscale.

A key non-technical challenge highlighted was the limited availability of manufacturing and fabrication facilities for research purposes – a common theme throughout the workshop.

Relation to Quality, National Importance and Capacity: The area is strong in the UK, but it is not yet internationally leading; the US, Japan and Switzerland lead. The UK is, however, a pioneer in niche robotic applications such as eye surgery and catheters/fibres for surgery. The wider UK communities in electronics, (macro) robotics and sensing, have clear leads internationally that could be capitalised upon to grow the micro-robotics area. Robotics is also a key future technology and a priority for the UK government. To open up this potential capacity, research silos need breaking and greater engagement across the microsystems community is needed. Attendees also highlighted the need for greater support to link low to high TRL research across publicly funded research.

Synergies: Research topic synergies identified included bio-inspired design, robotics, systems engineering. Applications included micro-robots for medical devices, space, offshore and hostile environments.

Example of UKRI EPSRC Investment: Wellcome UKRI EPSRC Centre for Surgical and Interventional Sciences

Annex 2: Attendee List

Speakers:

- Maisie England (EPSRC)
- Will Gompertz (EPSRC)
- Dr Firat Güder (Imperial College London)
- Dr Ian Sturland (BAE Systems)
- Professor Marc Desmulliez (Heriot-Watt University)

Attendees:

- Professor Alex Yakovlev (Newcastle University)
- Dr Almut Beige (University of Leeds)
- Dr Amal Hajjaj (Loughborough University)
- Professor Andrew Gallant (Durham University)
- Professor Andrew Holmes (Imperial College London)
- Dr Andrew Reid (University of Strathclyde)
- Professor Ashwin Seshia (University of Cambridge)
- Dr Christabel Tan (University of Hertfordshire)
- Dr Chun Zhao (University of York)
- Professor David Cumming (University of Glasgow)
- Dr Despoina Moschou (University of Bath)
- Dr Dimitrios Kontziampasis (Staffordshire University)
- Professor Doug Paul (University of Glasgow)
- Dr Elizabeth Rendon-Morales (University of Sussex)
- Dr Gerard Cummins (University of Birmingham)
- Dr Hamdi Torun (Northumbria University)
- Dr Hamed Farokhi (Northumbria University)
- Dr Hamza Shakeel (Queen's University Belfast)
- Professor James Windmill (University of Strathclyde)
- Dr Jamie Marland (University of Edinburgh)
- Professor Kirill Horoshenkov (University of Sheffield)
- Dr Konstantinos Glaros (EnSilica Ltd)
- Dr Laura Gonzalez-Macia (Imperial College London)
- Professor Lijie Li (Swansea University)
- Professor Manish K Tiwari (University College London)
- Dr Mark Everitt (Loughborough University)
- Dr Mohammad Esfahani (University of York)
- Professor Paul Maguire (Ulster University)
- Dr Ralf Bauer (University of Strathclyde)
- Dr Robert Kay (University of Leeds)
- Dr Sara Ghoreishizadeh (University College London)
- Dr Simon Bennet (University of Birmingham)
- Dr Tayebeh Ameri (University of Edinburgh)
- Dr Vishal Shah (University of Warwick)
- Professor Weiping Wu (Cambridge Ink Technology Ltd)
- Professor Yang Liu (University of Exeter)
- Dr Yoshishige Tsuchiya (University of Southampton)

We have respected the wishes of several attendees who did not wish to disclose their names.