Engineering for a Prosperous Nation Review

1st October 2019, London

Workshop Report

Background

What was it?

Engineering for a Prosperous Nation was delivered as a Big Pitch call in the Autumn 2017. This call was aimed at stimulating transformative Engineering research ideas aligned to EPSRC's four prosperity outcomes (A **Productive/ Resilient/ Connected/ Healthy** Nation) as highlighted in the 2015 Delivery Plan.

Why did we do it?

There were a number of aspects which led to the call:

- Many of the research area rationales, published as part of EPSRC's *balancing capability* strategy in 2017, included the desire for greater alignment of research to the prosperity outcomes and ambitions.
- There was a desire to encourage a greater breadth of community-led ideas to meet the delivery plan goals.
- Reflections from the 2017 Engineering Regional Meetings implied that EPSRC's prosperity outcomes were not fully understood by a majority of the Engineering community.
- Further output from the Engineering Regional Meetings highlighted "*There is little opportunity to support speculative, high risk ideas for Engineering research that are too nascent for standard routes"*.

What were our expectations?

- **Greater wealth of research** to show that EPSRC investments can contribute to a more prosperous nation (within delivery plan timescales);
- **Increased support** of high risk, speculative Engineering research (that are community-led feasibility projects that could inform future investments);
- **An increased understanding** from the Engineering community of how their research aligns to EPSRC's outcomes model;
- **An improved culture of ideas generation** is created within the Engineering community

Call Process

The Big Pitch process was one of several established approaches that EPSRC used to stimulate and encourage individuals to express their creativity and develop pioneering, potentially transformative research. *Previous calls include Ground and Structural & Water Engineering (2014); Nanoscale Design of Functional Materials (2013); Frontier Materials Manufacturing Research (2009)*

- Stage 1: Outlines (anonymous) – encourage equality, diversity and inclusion by focussing on idea rather than applicant track record, career stage or institution.
- Stage 2: 'Dragon's Den' style interview panel (s) – four parallel panels, with 'rovers'

- **Grants -** A portfolio of feasibility-type projects (up to £250k; 24 months) spanning the four prosperity outcomes
- **Timescales -** Launched in July 2017; Panels (and decisions) in November 2017

What did the call achieve at the outset?

- EPSRC delivered a £6.6m investment across Engineering, Healthcare Technologies and Energy themes over a very short timescale (under 5 months from call launch to grants being awarded)
- The call stimulated a large number of community-led project ideas (181 outlines received) where 28 individual projects were funded that directly relate to the four prosperity outcomes (5 Connected; 9 Healthy; 7 Productive and 7 Resilient)
- The funded projects covered 19 of the 20 ambitions across all four outcomes (only ambition C5 was not covered) (see table of projects and alignments on next page)
- A diverse range of institutions were involved: 39 universities submitted at least one outline; applicants from 17 universities received the funding.
- Reflections from panel convenors seemed to indicate that a large majority of the applicants were at Early Career stage rather than established. This is also apparent in the proportion of those successful projects led by applicants with Dr (86%) as their title, as opposed to Professors (14%). This is in direct contrast to what is generally observed in proposals submitted through standard mode.

	Title	PI	RO	P1	P2	P3	P4	P5	R1	R2	R3	R4	R5	H1	H2	H3	H4	H5	C1	C2	C3	C4	C5	TS
CONNECTED	CoTRE - Complexity Twin for Resilient Ecosystems	Guo	University of Warwick																					C
	RANDOMNESS: A RESOURCE FOR REAL-TIME ANALYTICS	Polydorides	University of Edinburgh																					C
	iSeat - Towards an intelligent driver seat for autonomous cars	Anvari	University of Southampton																					C
	Improving Protocol Standards for a more Trustworthy Internet	Perkins	University of Glasgow																					C
	Bandwidth and Energy Efficient Compact Multi-Antenna Systems for Connected Autonomous Vehicles	Karadimas	University of Glasgow																					B
HEALTHY	Q-NEURO: Diamond Quantum Technology for the Investigation of Neurological disease	Jackman	University College London																					C
	Healing Tissues via Programmable DNA Nanotechnology	Almquist	Imperial College London																					C
	REALiTY: REmoving Allergens with pLasma TechnologY	Walsh	University of Liverpool																					B
	Nanoparticle imaging method for drug discovery and cancer therapy in humans	Bayford	Middlesex University																					B
	Born Slippy: A Tribological Discourse on Hysterosalpingography as a Therapeutic Treatment for Infertile W	Dearn	University of Birmingham																					C
	Engineering Novel Imaging Technologies for Reproductive Health: Transforming IVF outcomes	Mahajan	University of Southampton																					B
	In-shoe sensory systems to assess and avoid diabetic foot disease	Culmer	University of Leeds																					B
	AUTOMATIC CELL FATE ENGINEERING USING MICROFLUIDICS DEVICES	Marucci	University of Bristol																					B
	Intelligent RF Sensing for Falls and Health Prediction - INSHEP	Fioranelli	University of Glasgow																					C
PRODUCTIVE	Artificial Transforming Swimmers for Precision Microfluidics Tasks	Montenegro-Johnson	University of Birmingham																					D
	When the drugs don't work... Manufacturing our pathogen defenses	Majewski	University of Sheffield																					C
	Engineering halide perovskites for artificial leaves	Eslava	University of Bath																					C
	Bioinspired green manufacturing of next generation energy storage materials	Patwardhan	University of Sheffield																					D
	Freeform Composites: Breaking free from the mould	Fairclough	University of Sheffield																					D
	Ahead of the Curve: Engineering Simulation for Computers of the Future	Lind	The University of Manchester																					D
	Renaissance of alloys: nanocrystalline bimetals	Polcar	University of Southampton																					B
RESILIENT	Carboglass: Transformative Engineering Materials for Reduced Energy and Waste Consumption...	Bingham	Sheffield Hallam University																					D
	Biopolymer treatment for stabilisation of transport infrastructure	Hughes	Durham University																					C
	Tackling AMR in Wastewater Systems with Sneaky Bacteria	Graham	Newcastle University																					D
	Harnessing Free Energy -the microbial way	Dolfing	Newcastle University																					C
	Development of A Novel Self-Healing Composite for Sustainable and Resilient Concrete Infrastructure	Zhang	University College London																					D
	Resilience-Based Design of Biologically Inspired Columns...	Kashani	University of Southampton																					C
	PLAIN-GG: Phase-Locked Atomic INterferometers for Gravity Gradiometry	Himsworth	University of Southampton																					C

The Review and Workshop

A commitment was stated in the call document to review the Engineering for a Prosperous Nation portfolio after approximately 12 months from the start of the projects to explore the opportunities to provide further funding to extend the research in progress and enhance the impact of the initiative. This workshop was organised to serve as a review and an exploration of the future of the initiative.

In addition to the overarching focus of the review, the workshop had a multiple aims and objectives:

- To provide opportunity to reflect upon whether the 28 funded projects met EPSRC's initial expectations.
- To present EPSRC's new Delivery Plan to the attendees to increase their understanding of how their research/future research relates to this and the evolved prosperity outcomes.
- To assist in determining whether it would be beneficial to provide similar funding routes in the future.

Prior to the workshop, attendees were asked to prepare a 5 minute presentation covering their research, impacts and outputs and alignment to EPSRC's prosperity outcomes. Full summaries of all of the funded Engineering for a Prosperous Nation projects can be found in the annex.

Workshop Agenda

10.30	Arrival (Tea/Coffee)
11.00	Welcome/Introductions
11.30	Project Presentations
13.15	Working Lunch
14.00	EPSRC Engineering Delivery Plan
14.30	Group Discussions
15.30	Closing Remarks & Networking with Tea/Coffee
16.00	Close

Summary of Outputs

Engineering for a Prosperous Nation Expectations Session

Attendees were asked to capture their thoughts and reflections on EPSRC's expectations, as set out by EPSRC in the 2017 call document. A list of the outputs provided by the attendees and information summarised from the presentations are captured below under each question posed:

Expectation 1: A greater wealth of research to demonstrate that EPSRC investments can contribute to a more prosperous nation

With reference to society, knowledge, people and the economy, please describe the different types of impact your research has had:

A broad range of impacts were identified from the projects, including:

- Journal and conference articles
- Patents
- New collaborations in industry and academia (international and national)
- Improved mobility across disciplines
- Contributions to reports, standards and roadmaps in the field
- News articles, radio and TV engagement
- Video abstracts
- Better visibility in the community
- Clinical involvement.

How has Engineering for a Prosperous Nation influenced the Pathways to Impact of your research?

- Helped to define research goals and targets;
- Helped to identify collaborators and create new opportunities, as well as early identification of stakeholders and collaborators;
- Facilitated a different way of thinking – more creative and innovative.

Expectation 2: Increased support of high risk, speculative Engineering research

How has Engineering for a Prosperous Nation encouraged you to pursue high risk, speculative Engineering research?

- It was short duration, small but enough money for proof of concept studies;
- A low effort application process and the interview etc allowed for more creative thinking and the effort to reward was in line – small effort for small amounts of cash;
- Allowed to pursue a risky idea that had been sat around and wouldn't have been funded through other routes;
- Allowed to be more ambitious and adventurous;
- Double-blind peer review encouraged this high risk, ambitious and adventurous culture of ideas generation.

Could this type of research have been funded through other mechanisms (e.g. standard mode)? What was the added value of applying to Engineering for a Prosperous Nation?

- The overall feeling here was that this scheme allowed EPSRC to fund high risk research which would not have been funded through Standard Mode;
- It was facilitated by the application process;
- Allowed the funding of TRL 0 ideas which industry wouldn't typically engage with;
- ECRs found it particularly valuable.

Expectation 3: Encourage an increased understanding from the Engineering community of how their research aligns to EPSRC's outcomes model

With reference to the outcomes model, how has your research contributed to a more prosperous nation?

- A number of the projects haven't yet contributed as such, but this has paved the way to allow them to apply for more funding now that they have proof of concept and will likely have an impact in the future.
- Many in the Healthy outcome have begun to contribute.

How has EPSRC's outcomes model influenced the direction of further research/succession?

- The overall feeling is that the outcomes have not influenced the research but more helped researchers to better frame their work in terms of making the nation more prosperous.
- The way research is framed/highlighted has been changed, and it has encouraged the community to think in terms of EPSRC's aims and how to link their research to it.

Is there a way in which research that contributes to UK prosperity could better encouraged?

- Have case studies publicised from this scheme;
- Streamline the EPSRC website so it is all clearer (too many priorities etc. on there is confusing);
- Post-research impact should be considered more often, rather than thinking about it before.

Expectation 4: Create an improved culture of ideas generation within the Engineering community

How has Engineering for a Prosperous Nation contributed to improving ideas generation within the Engineering community?

- It has opened up new areas of research/collaborations/multi-disciplinary collaborations for some;
- Has given an ability to embrace higher risk ideas and focus on application areas;
- Overall, the respondents said that the scheme allowed freedom of thought and removed the fear of it being too risky for the scheme.

Please detail any new connections, collaborations and opportunities that have arisen as a result of Engineering for a Prosperous Nation?

- A large number of new collaborators have been identified across multiple sectors, countries, disciplines and businesses;
- A small number of the research projects are still too low TRL for industrial involvement.

Outputs and Impacts Reports

In order to ensure outputs had been collected from all grant holders, we contacted those who were unable to attend the workshop, and have summarised these outputs and impacts of their grants below. The grant holders were asked to address the following questions in their report:

1. What impacts and outputs have arisen from your grant? This can include new collaborations, journal publications and all other types of impact.
2. How has the Engineering for a Prosperous nation affected your research and could your research have been funded through Standard Mode?
3. Has the research led to any further funding?

A summary of the responses to each of the above questions can be seen below:

What impacts and outputs have arisen from your grant? This can include new collaborations, journal publications and all other types of impact.

Impacts and outputs identified included:

- Journal papers
- Conference papers and presentations
- Supporting careers and progress of researchers
- New industry/academic collaborations
- Building collaborations with different sectors
- Establishing career independence/research team.

How has Engineering for a Prosperous nation affected your research and could your research have been funded through Standard Mode?

- The flexibility of the scheme offers the boost to develop ideas into ambitious projects which would have difficulty being funded through standard mode. Being able to apply for a project of 1 year duration to test whether general ideas work is extremely beneficial and reduces the risk of spending EPSRC money.

- The lack of necessity of in-kind industrial support means that the scheme is ideal for supporting ambitious, risky projects.

- The scheme encouraged speculative moves into new areas of research for several of the grant holders.

- Early Career Researchers benefit from the application process due to lack of focus on aspects such as track record. These grants are also beneficial to ECRs as they have helped grant holders form research groups.

Has the research led to any further funding?

- Many of the grant holders who were unable to attend are either in the process of developing proposals or have obtained funding from either EPSRC or elsewhere (e.g. British Council Award, ERC Starting Grant, R&D funding).

Delivery Plan Session and Table Discussions

At the workshop attendees were given a presentation on EPSRC's new Delivery Plan and the evolved prosperity outcomes. Following this, attendees were split into 4 groups covering the Productive, Resilient, Healthy and Connected outcomes (with Productive and Resilient combined) to discuss alignment to the evolved priorities and potential routes for furthering their research.

Alignment to the Prosperity Outcomes

The attendees were asked whether they felt that they now were better aligned to a different outcome. Whilst it was noted that a few felt that they were previously better aligned to Productive and now are more Resilience focussed, most still aligned to their initial outcome. It was also highlighted by a number of the grant holders that many of the individual projects have since evolved and branched into different directions so alignment to the original outcomes is not as strong as previously. Despite this, the general consensus was that the prosperity outcomes are broad and that there is often overlap between them. This was considered particularly prominent in Engineering where much of the research is considered to have relevance to Productive and Resilient.

The discussions also focussed on whether the attendees consider the prosperity outcomes and Delivery Plan when writing proposals and the level of influence this has. It was emphasised by the attendees that whilst the outcomes might not be the initial focus when writing a proposal, how aspects of a project relate to the outcomes and how best to highlight these in a proposal are considered. Therefore, a direct benefit of this scheme has been that those involved now have a greater understanding of the outcomes and how their research aligns to them.

Alternative and Further Funding

The discussions from this session also built upon the comments shared during the Expectations Poster session in terms of determining what the main routes for further funding being sought are.

The call provided a unique opportunity to encourage high risk, transformative research projects without clear routes to impact that was not suitable for standard routes. The attendees agreed that funded projects may not have been successful through standard mode partly because the projects focussed on research at low Technology Readiness Levels (TRLs) that precludes industry support and too high a risk that warrants funding through competitive means. However, the consensus was that much of the research was now in a better position to compete for EPSRC standard mode funding following the completion of the Engineering for a Prosperous Nation (EfaPN) projects. This is primarily because many of the perceived barriers to funding that previously existed (e.g. lack of industry support, few collaborations, no track record, and lack of proof-of-concept data) had been overcome through these duration of the proof-of-concept projects.

Whilst the qualitative evidence suggests the scheme has been successful in progressing transformational, high-risk research, offering the same level of funding to progress the research further was generally considered inappropriate as the timescales this would support would be too short to make significant progress and impact. Some of the grant holders expressed that a clear route for follow-on funding would be beneficial as they do not want to lose the progress made through their projects. This is particularly prevalent where productive industry partnerships had been formed.

Despite it being accepted that a similar repeat funding mechanism would likely not be valuable to current grant holders, it was emphasised that it would be beneficial for this type of proof-of-concept funding to be offered again for all of the Engineering community, due to the benefits it has had on

the EfaPN grant holders such as career progression (through establishing research groups), fostering new industrial and academic collaborations and encouraging a move into new areas of research.

Process Reflections

Attendees were given opportunity throughout the day to reflect upon the process for inviting and awarding the grants. Discussions around these primarily occurred during the table discussions and expectations poster session.

The expectations session highlighted that the process was particularly beneficial for academics without a track record in the area of research that they were pursuing and that normal routes would not have been feasible. Those that fell into this category also found that having a lack of industry support and extensive contacts did not negatively impact their application and that they have therefore been able to build and foster new collaborations through the project.

The use of *The Big Pitch* process to select these awards was also positively endorsed as it encouraged individuals to express their creativity through written and verbal means and develop pioneering, potentially transformative research based on an idea alone. It was emphasised by many that having the freedom to explore new ideas through a light-touch, low risk application process has encouraged high risk project ideas.

The general consensus from attendees at the workshop was that the call has stimulated a suite of greater transformational research than would otherwise have been funded through standard mode. There was some initial evidence of this gathered from the transformational scores allocated by the interview panels, as this appeared higher than typical scores seen for standard mode proposals. As such, the feedback from the workshop confirmed our expectations that this route provide enhanced opportunity for high risk, transformational research.

Conclusions and Next Steps

Conclusions

The workshop achieved its overall aims and objectives by:

1. **Demonstrating, through the evidence gathered, that the funded projects met EPSRC's initial expectations: e.g.**
    - The presentations highlighted that the research had direct impact upon and alignment to the Prosperity Outcomes;
    - The initiative encouraged more high-risk, speculative Engineering research and provided a route for funding that is not currently available for projects of this nature;
    - There was an increasing understanding of the Prosperity Outcomes within the Engineering community and an appreciation of considering these when writing new proposals;
    - The projects provided a vehicle for fostering new industry and academic collaborations within the Engineering community.
2. **Providing an opportunity to present the new Delivery Plan** to the attendees to increase their understanding of the evolved prosperity outcomes.
3. **Stimulated a wide range of discussions** on the benefits of similar funding schemes in the future and mechanisms to support further research beyond the scope of their existing projects.

Next Steps

1. Current grant holders generally acknowledged that the scale of these awards were ideal for generating transformative, proof-of-concept research and have helped in generating a track record and laid the foundations for follow-on funding. **EPSRC will consider supporting similar types of activity as part of the New Horizons initiative in the 2019 Delivery Plan to maintain a route for high risk, transformative research ideas, in addition to the usual support through standard mode.**
2. Whilst funding of the same scale was considered not enough to further progress these projects, several of the grant holders have since successfully sought further funding and others are in the process of doing so. EPSRC would **encourage EfaPN grant holders to seek follow-on funding through standard mode as this is considered the most appropriate route based on the evidence presented.** Whilst much of the risk can be mitigated through initiatives such as EfaPN, it should be noted that any application through standard mode should ensure that the level of ambition remains high.

Annex

Summary of Funded Proposals:

Connected Nation:

1. **EP/R041725/1, CoTRE - Complexity Twin for Resilient Ecosystems, Guo.**
   As we accelerate into the 21st century, our backbone engineering systems are becoming increasingly complex and connected. Many of our critical infrastructure ecosystems are comprised of interdependent sub-systems, each governed by complex non-linear dynamics and cascade interactions. The CoTRE project will build a mathematical mirror to the UK's critical infrastructure ecosystems. The "complexity twin" will be a world first attempt to understand the resilience of large-scale complex systems that increasingly face threats from man-kind and nature. The project will address the fundamental theoretical aspects of the stability of complex systems and work with a variety of critical infrastructure operators to develop short term and long term resilience investment strategies.

2. **EP/R041431/1, RANDOMNESS: A RESOURCE FOR REAL-TIME ANALYTICS, Polydorides.**
   The scope:

   Modern engineering relies on data and models to broaden our understanding of complex systems, devices and processes, through predictive and diagnostic analytics. Examples of this include fluid dynamic simulations for energy conversion, electromagnetic models in geophysical and environmental monitoring, mechanics in design of resilient infrastructures, acoustic and X-ray models for non-destructive testing and optical models in biomedical imaging. Traditionally, numerical computing has been at the forefront of engineering, however its embedding within the engineering process is still hindered by the complexity associated with realistic data models. Currently, process analytics, operate either off-line, on high performance computing infrastructure for accurate simulations and sophisticated data processing algorithms, or in real-time

   based on oversimplified problem specifications that yield some crude imperative information.

   The challenge:

   To empower data centric engineering in manufacturing and quality assurance processes with real-time, accurate modelling and data processing we take on the challenge of real-time, large-scale computing, by replacing the conventional way we perform algebraic computations with a more efficient randomised scheme. In the context of basic solution of linear equations for example, this approach randomly selects a small fraction of the elements in the matrices and the vectors involved, radically reducing the computational effort and time. What's more impressive than this, is that when optimally sampled, this computational efficiency is also complemented by a very small solution error, and thus by investigating ways that we can compute these optimal sampling distributions we can achieve massive computational savings, ultimately providing the productive sectors of the economy with an affordable solution for real-time modelling and data processing, without compromising the quality and accuracy of the sought information.

Main objectives:

The main objective of this project is to develop a new form of the popular finite element method by incorporating algorithms for randomised linear algebra. Through theory, analysis and computation we seek to prove a concept of randomised finite element method for simulating diffusion processes and solving the associated inverse data-fitting problems by investigating how the respective optimal sampling distributions can be computed and sampled in an efficient way.

Why does it matter?

The success of this project will make a measurable contribution on making accurate, high-dimensional computing portable and affordable to the broad engineering and manufacturing sector, allowing for real-time process monitoring and control even where high performance computing infrastructure is not available.

What difference will it achieve?

Our novel framework of data analytics aims to provide prompt and accurate insights into complex and dynamic data and models. In a manufacturing process this will lead to a rise in productivity, monitoring quality of services and products, as well as reduction of operational costs and waste. We also foresee that these advances will find application in the broader engineering sector as well as having an impact health informatics to enable simultaneous imaging and therapy for cancer patients and national security in being able to detect and screen in real time against threads.

3. **EP/R037795/1, iSeat - Towards an intelligent driver seat for autonomous cars, Anvari.**
According to the most optimistic predictions, the first commercially available fully-autonomous cars are expected in 2040 offering the consumer a full end-to-end journey. These self-driving vehicles will be equipped with technology allowing autonomy Level 5 in which there is no interference required by the human. The concept of autonomy levels was first published by the international Society of Automotive Engineers in 2014. The report defines six levels of autonomy that automakers would need to achieve on their way to building the no-steering-wheel self-driving bubble pods of the future reaching from the fully-manual Level 0 to the fully-autonomous Level 5.

In the race towards the first commercially available fully-autonomous car, the majority of cars on UK roads will be equipped with technology that allows Level 3 or 4 autonomy over the next two decades. Drivers will be provided with increasingly sophisticated features such as lane-keep and steering assist. These semi-autonomous cars might be able to transport the driver autonomously on sections of a journey. However, the driver is required to take control occasionally between different levels of autonomy when required to complete an end-to-end journey. These transitions between autonomy levels cause safety concerns, as the driver might not be fully aware of the surrounding situation and the enabled autonomy features instantly.

This project proposes a new interface design for semi-autonomous cars called iSeat. This system is fundamentally different compared to current systems (such as Tesla's Autopilot or

DistronicPlus by Mercedes) using visual or auditory indications which might be mentally overloading and distracting for the driver. iSeat is an intelligent driver seat acting as a co-pilot measuring the current mental and physical engagement of the driver and allowing safe, coordinated and timely transitions between different levels of autonomy. Of particular significance is the driver seat made of robotic structures serving the feedback purpose as well as providing monitoring capabilities through direct contact with the human during any level of autonomy: Tactile sensation can be fed back to the driver, the seat ergonomics and comfort can be changed and the robotic structures can measure the pressure distribution of the driver's weight. iSeat sensing information will be fused with multi-modal sensing data from electrical activity produced by skeletal muscles (Electromyography (EMG) signals) and in the driver's brain (Electroencephalography (EEG) signals), and input from vision cameras regarding the driver's posture and the point of gaze (i.e. where the driver is looking). This real-time knowledge will be classified through machine learning and affective interaction techniques in terms of the awareness state of the driver. Personalised feedback will be provided (i.e. tactile sensation, stiffness feedback, change of the driver seat ergonomics/comfort, visual/auditory feedback) to support the driver so that safe, timely, effective and intuitive transitions between different autonomy levels can be completed.

The iSeat system builds upon a complete re-think of the manner in which humans interact with autonomous cars. The smart combination of sensor systems, machine learning, affective computing, human factors, haptics and robotics will result in a bi-directional human-machine cooperation that is safe, intuitive, effective, and personalised.

4. **EP/R04144X/1, Improving Protocol Standards for a more Trustworthy Internet, Perkins.** This project will make the Internet's infrastructure and applications more reliable and secure, more trustworthy and less vulnerable to cyber attack, by improving the engineering processes by which the network is designed. The Internet comprises a large number of laptops, smartphones, and other edge devices, connecting to servers located in data centres around the world via numerous interconnecting links and switching devices. To make this work, all the devices must agree on how they should communicate. Thatis, they must speak a common language, known as a "protocol" that describes the format of the information that is sent and the operations to be performed. There are many such protocols, describing the different types of communication. For example, the HTTP protocol describes how browsers fetch pages from websites. To ensure interoperability between devices from different manufacturers, these protocols are described in a series of standards documents, published by organisations such as the Internet Engineering Task Force (IETF). These standards are developed incrementally by teams of engineers working over several months, or perhaps years, to produce a written specification that describes how the protocol should work. Despite the best efforts of those developing the standards, however, the results are often found to contain inconsistencies and ambiguities. These can lead to devices from different manufacturers failing to work together, due to differing interpretations of the standard, and in the worst cases can lead to vulnerabilities that open devices up to cyber attack. Much of the reason for these inconsistencies and ambiguities is that the protocol standards are written in English, and hence there's no automated way of checking them for correctness. Researchers have proposed ways of describing protocols using methods (known as "formal languages") that are more like computer programming languages, and that would allow automated consistency checks to be made, but these have not been widely adopted by the standards community.

This project will study the social, cultural, and educational barriers to adoption of these new techniques, to understand why standards continue to be written in English. We will explore the perceived limitations of the alternatives, to understand why they've been adopted in certain niches, and for certain purposes, but are not used more broadly in standards development. We'll then formulate a model for the adoption of formal languages and their supporting tools in the protocol standards community, and use it identify areas that are ready to increase use of such techniques in their standards. Finally, we'll use the knowledge gained to propose formal languages that are designed to fit the way the standards developers work, and begin the process of introducing these into the standards process, to improve protocol specifications and make them less vulnerable to attack. The work will be conducted in the IETF, since it's the key international technical standards body developing Internet protocol standards.

The aim is to improve the quality and trustworthiness of the standards that the IETF develops, and increase security, robustness, and interoperability of the Internet. The novel engineering research idea we will explore is that formal languages need to be adapted to the community of interest. It is not enough that they help solve the technical problem of how to specify a protocol: they must do so in a way that fits the expertise and culture of those who need to use them. Research into structured approaches and formal languages for protocol design has not yet considered the nature of the standards process, and hence has not seen wide uptake. We start with a deep awareness of the standards process, consider social and technical barriers to uptake, and propose new techniques to improve the way standards are developed.

5. **EP/R041660/1, Bandwidth and Energy Efficient Compact Multi-Antenna Systems for Connected Autonomous Vehicles, Karadimas.**

Autonomous driving is a key enabler for Intelligent Transportation Systems (ITS), which are expected to have major impacts on several environmental, economic and social aspects. ITS promise to relieve driver from tedious tasks, improve driving efficiency and safety and reduce traffic jams, injuries and gas emissions.

In ITS, seamless communications between vehicles are required and vehicular ad hoc networks (VANETs) will emerge to support autonomous driving. In VANETs, vehicle-to-vehicle (V-V) and vehicle-to-infrastructure (V-I) communications take place via wireless devices called on-board units (OBUs). OBUs are designated to operate under the 5.9 GHz dedicated short range communication (DSRC) standardized technology. Antenna systems, as part of OBUs, are responsible for transmitting and receiving the electromagnetic wave which carries the useful information message. Antenna systems are electromagnetic designs which are connected to specialized RF circuitry. In turn, such circuitry processes the information message before the transmission and after the reception by the antennas. The complete system includes the wireless vehicular environment (or vehicular channel) in which the electromagnetic wave propagates along the way from the transmitting to the receiving antenna. Such environment is inherently very complex and rapidly time varying due to its physical propagation mechanisms including three-dimensional (3-D) scattering, obstructed line-of-sight (LOS) and fast mobility of transmitter, receiver and surrounding objects (e.g., mobility of other vehicles).

Multi-antenna systems include many antennas operating together in order to increase communication performance in complex wireless environments. Accordingly, compact multi-antenna designs that perform optimally and can be packed in the limited OBU space become of paramount importance to support vehicular communications. Such designs should take into account a series of factors as imposed by the RF circuit, in which the antenna is connected and the surrounding wireless vehicular environment, in which the information message is transmitted and received. We have to exploit every potential the vehicular channel offers in order to maximize performance. The termination RF circuit characteristics affect performance as well and have to be taken into account and compensated at the early design stage. The proposed research activity will incorporate both the characteristics of the vehicular channel and termination RF circuit to derive optimal compact multi-antenna systems for OBUs. Thus, complete "RF circuit/printed multi-antenna/vehicular channel" optimized end-to-end systems will arise. Optimization will take place by maximizing the bandwidth efficiency first, as a standard key performance indicator (KPI). Optimization adopting the energy efficiency KPI will then follow. Such KPI will be employed for the first time to evaluate performance of realistic compact multi-antenna systems.

The description of concepts of operation (CONOPs) and KPIs with respect to the particular features of vehicular environments constitutes the first step. The adoption of a generic vehicular channel model, adaptable to any wireless environment and frequency of operation, will enable the design of optimized DSRC-5.9 GHz and mm-wave-60 GHz multi-antenna systems. Assessing the feasibility of using mm-wave frequency bands for vehicular communications will be one more achievement of the proposed research activity. The last step will be proof-of-concept demonstrators for both DSRC and mm-wave optimal multi-antenna systems.

While the objective here is to present optimal "RF circuit/printed multi-antenna/vehicular channel" end-to-end systems for vehicular communications, this project could benefit the development of future 5G mm-wave and massive MIMO systems.

Healthy Nation:

1. **EP/R034699/1, Q-NEURO: Diamond Quantum Technology for the Investigation of Neurological disease, Jackman.**

   Understanding the function of the brain is one of the most significant challenges of the 21st century. Vast numbers of the human population face the prospect of neurodegenerative disease (such as Alzheimer's); numbers that will only get higher with ever-increasing lifespan, in-part due to success in other branches of medicine and improvements in healthy living conditions. Neurogenerative disease is devastating for both the patient, and his/her family and friends, who progressively 'lose' the one they care about. Moreover, societal and economic costs associated with the care regime needed for such patients are significant. The challenge is two-fold by nature of the immense complexity of the brain, contrasted with the minute underlying electromagnetic fields that interconnect individual cells. Unfortunately, there is a lack of methods to detect signalling processes with the desired sensitivity and sufficient spatial resolution, making the challenge of understanding the brain's complexity near insurmountable. Current state-of-the-art techniques monitor fluorescence changes of voltage dependent indicators or use electrical probes to measure voltages across cell membranes. At large scales, SQUID magnetometers are used for magnetoencephalography (MEG), but are insensitive to single nerve impulses and come at great financial cost. Each method has limitations in one or more of the following categories: signal to noise ratio, temporal resolution and spatial resolution. Hence there is a major need of revolutionary methods to overcome these barriers. Q-NEURO aims to fill a major, outstanding need in neuroscience research in such a revolutionary manor.

   Q-NEURO will develop a novel imaging method to enable the detection of individual signalling events in neuroscience. The biosensor is based on quantum engineered diamond with properties that make it an unrivalled sensor for biology. Fluorescence microscopy will be used to readout an array of spins in diamond, which in turn will detect the magnetic fields produced during neural signalling. The spins are associated with the nitrogen-vacancy defect centre in diamond, a quantum coherent spin system allowing for ultrasensitive magnetic detection under ambient conditions.

   The quantum-bio sensor developed by Q-NEURO will enable: (i) imaging of individual action potentials from neurons with high spatial resolution down to the nanoscale, (ii) real-time detection of action potentials with sub-millisecond temporal resolution, (iii) wide field-of-view monitoring of neuronal signalling events in two dimensional networks.

2. **EP/R041628/1, Healing Tissues via Programmable DNA Nanotechnology, Almquist.**
   Growth factors are powerful biological proteins that cells produce and release. They have a key role in instructing our cells how to grow from one cell as an egg into approximately 30 trillion cells that are arranged in a coordinated fashion to create a person. Their influence also continues throughout our lives; if tissues are damaged such as a broken bone or wound on our skin, growth factors coordinate how our tissue heal. Because of this powerful influence, growth factors are highly attractive substances to use as therapeutics to promote tissue repair. While several are used in clinics around the world, their efficacy, safety, and impact are all far from being optimal due to sub-optimal efficacy and a high cost of production. Therefore, in order to truly realise their potential as therapeutics, we need new

strategies that revolutionise how we use growth factors clinically.

In this proposal, we will combine aspects of materials science, nanotechnology, and biology to develop a transformational approach to using growth factors as therapeutics. Our approach relies on designing novel nanotechnology-enabled materials that actively harvest growth factors from within the body to then use as therapeutics to heal tissues. This strategy will eliminate the need to produce expensive proteins, dramatically reducing the cost of treatment. Furthermore, it will enable the adaptation of previously approved therapeutics to new areas in tissue repair, speeding up the development of new treatments while also minimising production expenses.

We will demonstrate the ability of our new approach to heal critical size bone defects - that is, bone defects that are too large to naturally heal on their own. This data forms a key component of justifying the translation to the clinic, making this proposal instrumental in bringing this exhilarating new technology to the bedside.

3. **EP/R041849/1, REALiTY: REmoving Allergens with pLasma TechnologY, Walsh.**
Using this award a disruptive technological solution will be developed to alleviate the suffering of millions of people across the UK. It is envisaged that the developed device will be deployed in households and offices across the country to significantly reduce the concentration of airborne allergenic agents from within the indoor environment; thus making a significant contribution to the general wellbeing of over 12 million allergy sufferers in the UK. This disruptive technological solution will reduce the burden of allergy on the UK economy, which is estimated at around £7.1 Bn per annum through lost productivity and a further £311 million per year through the use of NHS resources.

   The project proposes the development of a Cold Atmospheric pressure Plasma (CAP) solution that is capable of simultaneously targeting multiple allergenic agents and overcomes many of the drawbacks associated with current approaches. To ensure widespread uptake and therefore maximise the impact from this research, the developed technology will be packaged as a low-cost and energy efficient consumer appliance, suitable for continuous use within the home.

   Technological development will not be easy nor risk free; however, the reward for overcoming these challenges will be a substantial improvement in public health and UK prosperity. To succeed, the outcomes of multiple RCUK funded research projects will be brought together to form a unique engineering solution which will be co-developed in collaboration with a forward-thinking UK-based industrial partner.

4. **EP/R04192X/1, Nanoparticle imaging method for drug discovery and cancer therapy in humans, Bayford.**
A novel nanoparticle imaging method for drug discovery and cancer therapy in humans will be created based on the combination of gold nanoparticles (AuNPs) as contrast agent, activated with radio-frequency (RF) and imaged with electrical impedance tomography (EIT). This would use the advantage that EIT is very sensitive to impedance change due to temperature changes from the RF activation of the AuNPs. It would have the potential to replace positron emission tomography (PET) imaging with the advantage of no ionising radiation, lower cost and the high temporal resolution of EIT. This would have a wider range

of applications including tracking nanoparticles used to target cancer cells and drug discovery. Key to their use is the ability to target the desired cells for therapy; at present transmission electron microscopy (TEM) or photo-thermic microscopes can be used to image them on cell lines or in some case samples removed from the patient but not in vivo. Technology like PET uses ionising radiation and MRI does not use AuNPs, as they are paramagnetic and would require many images to track the particles, which would not be cost effective. The new imaging technology could also be combined with radiotherapy to confirm the location of the AuNPs. Researchers have investigated the concept of kilovoltage radiosurgery with AuNPs for AMD (Age-related Macular Degeneration). They concluded that a prescribed dose of x-ray radiation could be delivered using almost half of the radiation when compared to a treatment without AuNPs allowing reduction of the dose delivered to the neighbouring organs such as the retinal/optic nerve by 49%.

Nanoparticles have been suggested for a range of clinical applications, including as contrast agents, for drug delivery and for treatment or therapy. Nanoparticles may be delivered to the patient by injection, by ingestion or by topical application to the skin, for example. Nanoparticles are constructed to perform a function in the body, for example to reach a particular target in the body such as an organ or a tumour. Once at the target, the nanoparticles may deliver a payload or play a role in some other function such as imaging or therapy. Thus, for example, if the nanoparticle is to target a tumour, cancer biomarkers may be attached to the scaffold core. Alternatively, antibodies to specific bacteria may be attached to the NPs in order to detect sepsis.

The ability to track drug delivery by attaching a nanoparticle in the human body or using AuNPs to kill cancer cells would transform cancer treatment and other conditions, for example, if cancer metastasises then AuNPs could prove a method of destroying cancer cells. Many drugs, even those discovered using the most advanced molecular biology strategies, have unacceptable side effects due to the drug interacting with healthy tissues that are not the target of the drug. The goal of a targeted drug delivery system is to prolong, localize and target however roughly 99% of the drugs administered do not reach the target site. Side effects limit our ability to design optimal medications for many diseases such as cancer, neurodegenerative diseases, and infectious diseases. Also at present technologies to track drugs use mass spectroscopy and animal experiments requiring large scale computing to provide only one image of the accumulation of the drug. The novel approach proposed in this would revolutionise this and could provide hundreds of images a second if needed. This project has considerable potential to optimise targeting.

5. **EP/R041407/1, Born Slippy: A Tribological Discourse on Hysterosalpingography as a Therapeutic Treatment for Infertile Women, Dearn.**

Blocked fallopian tubes are a common cause of female infertility. When seeking treatment for this, the first stage of any intervention will be a search for tube blockages. This procedure involves inserting a dye into the uterus that can then be used to screen how well the tubes are open using x-ray. This medical technique is called hysterosalpingography. The dye or contrast used is either a poppy seed oil based emulsion or water. A recent study led by Prof. Ben Mol at the University of Adelaide has shown a 10% increase in the rates of pregnancy and births for women who received the oil-based contrast. This is a remarkable result given that more common fertility treatment such as Intrauterine insemination raises pregnancy

rates by 1 or 2 %. The underlying mechanisms, however, that explain how fertility is enhanced are not clear. It has been suggested that tubal patency testing with an oil contrast flushes debris and dislodges mucus when the fallopian tubes are undamaged. This does not explain why water does not exhibit similarly impressive effects.

The transport of the ovum (or oocyte) from the ovary to the womb is essentially a tribological process. Poppy seed oil is composed, amongst other things of fatty acids and esters both of which are very good at improving the frictional response, or lubricity, of a given system. Good lubricity may help the oocyte to move more easily through the tube, may the prevent the formation of debris in the tubes, prevent the fallopian tubes from closing and/ or aid sperm mobility. All of these effects can be explained by understanding tribology of the system.

This research sets out an ambitious goal of measuring the tribological properties of this Mol's observed phenomenon. At its centre is the use of a novel method to nondestructively measure the frictional properties of an oocyte in transit through a simulated fallopian tube using direct observation, mechanical modelling and a machine-learning algorithm.

Infertility is a big problem. 186 million women in the developed world are affected by it, equivalent to one in four adults. By understanding the underlining tribology of HSG therapy and the interaction between specific components within the contrast, the surfaces within the reproductive and the physiological reproductive process, a new tailored and extremely effective approach to the treatment of female infertility could be developed.

6. **EP/R041814/1, Engineering Novel Imaging Technologies for Reproductive Health: Transforming IVF outcomes, Mahajan.**

The aim of this proposal is to take cutting edge imaging techniques and use them to improve the outcomes of assisted reproduction treatment procedure also known as in-vitro fertilisation or IVF. Whilst IVF has been used for almost 40 years now, it remains a largely unsuccessful procedure (only 26% of cycles end with a live birth) and is expensive for patients to use (~£5000 for a basic cycle, typically >1 cycle is needed). During the procedure, a woman's eggs are taken and fertilised by sperm in the clinic. They are then incubated for several days and the best embryo is selected and returned to the patient. The main problem is that the embryologist has very little information helping them to choose, and does not know which embryo is the best.

We know some of the more common causes of failure include embryos that have the wrong number of chromosomes (DNA material) and embryos that that are not metabolising at the correct rate - this is difficult to determine without destroying the eggs. We are proposing two new imaging techniques to address these problems as follows: Firstly, we will use coherent Raman microscopy (CRM). This allows us to image specific structures within cells by targeting less damaging lasers to match the vibrations of certain types of molecules. In this case we propose to target the DNA allowing us to see inside the cells and image the chromosomes. We can therefore watch the chromosome divisions inside growing embryos and be alerted if the divisions are abnormal. Secondly, we will use the technique of two-photon fluorescence (TPF). With this we can image molecules that are part of the metabolic pathway in cells. Their ability to emit light changes depending on the metabolism of the cell

and so we can determine the metabolic activity within each cell of an embryo, allowing defective ones to be discarded early on and the best ones to be selected.

This proposal aims to combine these two imaging techniques into a single bench-top embryo-imaging devic. The device will be ground-breaking in that it will combine two useful diagnostic readings, it will only use near-infrared light, which is far less damaging than the current visible light microscopes, and it will use a light-sheet configuration. This novel configuration means the embryo is illuminated by a plane of light from the side, instead of the conventional focussed laser spot. This approach is again far less damaging than the conventional method and also speeds up image capture. The end result is a much healthier way to image an embryo. In this proposal we will develop the two new techniques, and combine them in the novel light-sheet microscope configuration. We will then test their ability to distinguish the best from the worst embryos, initially using mouse embryos as a test model. Later and with the required ethical permissions we will test the device on donated, or discarded human eggs.

Our vision is that the embryologist will be able to peer inside the embryo and have a wealth of information available to them. They will then only transfer the best embryos to the patient, increasing greatly the chances of success and reducing the suffering and financial difficulties of repeated failures to conceive that are currently experienced by IVF patients. Since this is now emerging as a global issue, there is an increasing demand for IVF worldwide and consequently the need for an improved technological solution. This presents a huge business opportunity as well besides the fact that it will reduce the distress, treatment burden and costs for patients.

7. EP/R041776/1, In-shoe sensory systems to assess and avoid diabetic foot disease, Culmer.

This project concerns exploratory research to develop a new type of tactile (touch) sensing technology and investigate its exciting potential to transform treatment of Diabetic Foot Ulcers - a huge clinical challenge worldwide.

Background: The project has been designed to address the UK strategic research ambition to 'Optimise Diagnosis and Treatment' of Diabetic Foot Disease. Diabetes affects over 4.5m of the UK population and the condition acts to affect soft tissues in the body, notably the feet, leading to formation of ulcers. Studies estimate that over 2.5% of those with diabetes will have a diabetic foot ulcer (DFU), a hugely debilitating condition which has a significant impact on personal quality of life and costs the NHS up to 1.13billion each year. For effective diagnosis and treatment of DFU it is important to understand the behaviour of the sole of the patient's foot. This is a challenging task and while modern assessment methods use in-shoe digital measurement systems they are expensive and measure only a small part of the information that would be clinically useful.

The novel idea at the heart of this project is to develop tactile sensing technology based on small electronic coil elements which can be easily printed onto flexible films using mass manufacturing techniques. Sensor films will be composed of a bottom coil layer, a thin middle layer which can be squashed and a top contact layer. Crucially, this concept allows 1) pressures to be measured in different directions (side-to-side, fore-back, up-down) and 2) a grid or 'array' of sensing elements to be placed across a film, so measurements can be

obtained at more than one location.

The sensing technology will be applied to develop a prototype 'next-generation' in-shoe assessment system for DFU with the ability to simultaneously measure pressures in different directions. A sensing 'sole' will be developed using a grid of sensing elements placed at key regions of the foot combined with a mobile data logging system. While the idea is ambitious it has the potential to transform assessment and treatment of DFU. It will enable improved measurements to guide diagnosis and treatment at lower cost and with the potential to produce personalised systems for long-term monitoring of 'at-risk' patients.

The project will use of a series of collaborative placements to ensure it is clinically relevant, has a commercial future and to promote the use of engineering science to advance healthcare. We will work with industry partners and manufacturing experts to help develop a future commercial product. We will work closely with clinical partners to understand first-hand DFU treatment and how this technology should be developed accordingly. We will run research internships in which undergraduate students from Leeds and India collaborate on the project, notably exploring how this technology could be adapted to benefit healthcare systems in Low and Middle-Income Countries.

The outcomes from this work will help make a positive impact to society, benefit the research community, and help expand the UK economy. We will work closely to involve the general public with our work to demonstrate how engineering science research is relevant and crucial to society. We will present at public events (e.g. Science Festivals) and produce public demonstration systems to showcase our research.

For society, the in-shoe sensory technology developed by this research will directly help improve diagnosis (through affordable measurement technology) and accelerate treatment (through detailed, personalised assessment).

For the UK, advances in Sensor Technologies are central to UK Government's strategy on Robotics and Autonomous Systems (RAS), defined in the Innovate UK RAS2020 roadmap and linked to needs for international competiveness, productivity and economic growth.

8. **EP/R041695/1, AUTOMATIC CELL FATE ENGINEERING USING MICROFLUIDICS DEVICES, Marucci.**

Stem cells are pluripotent cells that can both proliferate indefinitely producing cells identical to them, and specialise into more mature cells types. In adults, stem cells have a repair function in case of damage; adult stem cells are currently used in medical therapy. The major limitation of adult stem cells' medical applications is their low availability, and the difficulty to expand them in culture.

Such issues were thought to be overcome thanks to the astonishing discovery of reprogramming by the Nobel Prize-winning Shinya Yamanaka: differentiated (i.e. somatic) cells can be programmed back to a stem-like state, obtaining the so-called induced Pluripotent Stem Cells (iPSCs). iPSCs can be subsequently converted into any cell type, to be used for regenerative and personalised medicine purposes. In Japan, the first clinical trial using iPSC-derived cells in humans is on going to cure age-related macular degeneration.

iPSC therapy still faces, however, major challenges: it is difficult to reprogram somatic cells and maintain iPSCs in the pluripotent state; also, iPSC differentiation is often inefficient.

In this research, we aim at applying state-of-the-art Synthetic Biology and Control Engineering tools to automatize and optimise the manufacturing of iPSC-derived cells. We will prove, using mouse cell lines, that each of the 3 mentioned challenges can be addressed if, while providing inputs that trigger pluripotency or differentiation, cells are continuously observed and inputs are consequently "adjusted" to obtain the target phenotype. This closed-loop strategy will be implemented by means of microfluidics and microscopy, that allow monitoring in real-time living cells, comparing relevant cellular outputs to the target one and applying control algorithms that allow acting on the cells to minimise the error.

While proving that, by "closing the loop", it is possible to automatically control stem cell fate, we will provide a platform that allows, at the end of the experiment, to retrieve from the microfluidics device the desired cell type with high efficiency and reproducibility.

9. **EP/R041679/1, Intelligent RF Sensing for Falls and Health Prediction – INSHEP, Fioranelli.**

The proportion of elderly people is increasing worldwide. In the UK, the Office for National Statistics estimates that "The number of people aged 75 and over is projected to rise by 89.3%, to 9.9 million, by mid-2039; the number of people aged 85 and over is projected to more than double, to reach 3.6 million by mid-2039; and the number of centenarians is projected to rise nearly 6 fold, from 14,000 at mid-2014 to 83,000 at mid-2039". Consequently, conditions such as diabetes, obesity, dementia, Parkinson's disease are expected to increase their incidence, with more and more people affected by multiple conditions at the same time (multimorbidity).

Furthermore, statistics in the UK show that "falls and fractures in people aged 65+ account for over 4 million hospital bed days each year in England alone, and the healthcare cost associated with fragility fractures is estimated at £2bn a year". Physical consequences of fall events (fractures, contusions, open wounds, abrasions, strain, and concussions) often require treatment at A&E departments if not hospitalisation, but they also lead to anxiety and loss of independence. All these reduce the quality of life of the people affected and of their families, as well as generate public costs for healthcare provision.

Our project will investigate how radar technologies will help vulnerable individuals (older people and people with cognitive or physical impairments, or with multi-morbidity conditions) preserve their independence and quality of life, and provide caregivers and health professionals with individualised information on each patient. In practical terms, our system will monitor activity levels over longer periods of time to detect early signs of cognitive and functional decline, providing not only prompt detection of critical events (e.g. falls, strokes), but also predicting these events from indicators in the data that will enable individualised prompt treatment and intervention from health professionals.

Radar snsors transmit and receive electromagnetic waves similar to those used by common devices such as Wi-Fi routers, and the analysis of the received echoes can provide information on how and where a person moves. Radar offers the advantage of providing

contactless and non-intrusive monitoring, with no need for the end-users to carry or interact with devices, or alter their behaviour, and no need to record direct optical images of them. This makes these sensors attractive as a potential alternative to wearable sensors and conventional video-cameras, or as a complementary sensor to those ones.

Our project will combine cutting-edge research in the field of electronic engineering and machine learning, with end-users engagement from the very early stages (older people, caregivers, health professionals, community members). We will take into account their inputs, requirements, issues, attitudes in relating with our technology, and inform the design and technical choices while developing our system. This will enable to address potential users' acceptance issues and barriers to the development and adoption of the technology, an element of strength to maximise the impact of our proposal.

Productive Nation:

1. **EP/R041555/1, Artificial Transforming Swimmers for Precision Microfluidics Tasks, Montenegro-Johnson.**

   Imagine a world where tiny objects could self-assemble from component microbots to perform a specific task, and then disassemble when no longer required, where chemotherapy is delivered directly to the site of tumours, and where heart surgery amounted to a simple injection. This is the great promise of a novel technology; the artificial swimming micromachine.

   However, the current generation of swimming micromachines has a fundamental flaw; it is not possible to effectively control individuals within a large group. Without this precision control, it will be impossible for this technology to perform precision tasks such as targeted drug delivery.

   But Nature has found myriad ways to overcome the challenge of propelling and steering microorganisms through complex environments. Inspired by Nature, this project will design swimming micromachines that can transform shape in order to perform different functions. The novel ability to transform will allow micromachines to transcend this control barrier, and realise the potential of this exciting technology.

   Developing a prototype of these microtransformers is a complex task that spans traditional scientific disciplines, and will only be possible with new mathematical theories and cutting-edge materials that can be "programmed" to remember specific shapes.

   The initial design to be used as a proof of concept will be a flexible filament, with both ends coated in platinum. When placed in hydrogen peroxide, the platinum will catalyse its reduction into water and oxygen, causing a flow at the surface of the filament. If the filament is straight, this flow should act as a pump, if it is bent in a "U"-shape, the filament should translate, and if bent into an "S"-shape, it should rotate. Using ultrasound to switch the filament between these preprogrammed shapes, the micromachine would then be able to navigate complex environments using a series of straight runs and on-the-spot reorientations, just like bacteria.

   The project will take this novel idea, and develop new mathematical tools to model the coupled elastic, fluid, and chemical dynamics of slender filaments in order to optimise this initial design, and conceive new designs with greater functionality involving multiple filaments and ribbon-like structures. At the same time, experiments will develop a lab prototype that will be used to test and refine the theory.

   By the end of the project, this prototype will be sufficiently developed to begin commercialisation of the technology for industrial use, and to begin the development of a "biocompatible" prototype for minimally-invasive medical applications.

2. **EP/R036748/1, When the drugs don't work... Manufacturing our pathogen defences, Majewksi.**

The average person comes into contact with millions of bacteria every day, especially in areas with a high throughput of people. In the majority of cases we are peacefully oblivious, with this having little tangible effect on our lives. However, where a person has a lower immune system than normal these bacteria can become deadly. With an increase in drug-resistant strains of bacteria, preventing them from settling or spreading therefore become a critical challenge, particularly in hospital wards and care homes housing the most vulnerable members of our population. 'Normal' products and surfaces all become potential breeding grounds for bacteria, and therefore potential routes to infection. Addressing this issue is the main focus of this work.

The overall vision for this research is the production of medical and consumer products and devices with inherent anti-bacterial properties. For the majority of products for which this is important, standard techniques include rigorous (and often complex) cleaning or sterilisation procedures, or coating the product with an anti-bacterial compound. Whilst these provide a level of protection, each has limitations; for example cleaning and sterilisation procedures can be subject to human error and coatings may become scratched or damaged, leaving some areas unprotected. Products with complex geometries (including those incorporating some degree of personalisation), are of great interest in the healthcare sector but also present the greatest challenge in ensuring consistency of anti-bacterial protection.

By introducing anti-bacterial behaviour into a product directly, many of these issues could be reduced or eliminated. This project will provide crucial early-stage investigations into the possibility of combining cutting-edge Additive Manufacturing (3D Printing) techniques with a silver-based anti-bacterial compound in order to produce highly complex products incorporating anti-bacterial properties. Additive Manufacturing techniques are well-recognised for their ability to produce complicated geometries with little of no cost penalty, and the anti-bacterial properties of silver have been known for millennia. Bringing the two together presents a real opportunity to provide a significant impact on our ability to guard against infection.

This project will investigate the potential of this technique for applications in a wide range of areas including medical devices (e.g. endoscopes or other intrusive devices used for multiple patients), general hospital products subjected to high levels of human contact (e.g. door handles or taps), oral health products (e.g. dentures) and consumer products (e.g. mobile phone cases or personalised shoe insoles). Further projects are planned in each of these areas, following successful proof of concept here.

3. EP/R035407/1, Engineering halide perovskites for artificial leaves, Eslava.

The manufacturing of artificial leaves that reproduces at larger scale what plants do when they form carbohydrates by natural photosynthesis is a grand ambition for the creation of a sustainable society. Success has the potential to cease our dependence on fossil sources for polymer syntheses, pharmaceutical manufacture, and transport applications (e.g. fuels in cars) and instead allow us to use atmospheric or flue gas CO2. The Royal Society of Chemistry emphasises this potential in the recently launched report "Solar Fuels and Artificial Photosynthesis" (2012). In line with this, the US Department of Energy has identified the photo-driven conversion of CO2 as a priority research direction and The

Institution of Chemical Engineers (IChemE) has recently launched a new special interest group dedicated to alternative and renewable energy.

Many active semiconductor photocatalysts such as titania and zinc oxide have been proven to photocatalytically convert CO2. However, they offer low yields of products under sun irradiation due to their intrinsic limitations such as low solar absorption and short lifetime of photoinduced charges. To make CO2 solar photocatalytic reduction a viable and commercial technology further research on novel materials is needed.

This research project aims to develop artificial leaves with halide perovskites, novel materials of unprecedented success in photovoltaics that remain unexplored in photocatalysis because they suffer from chemical and structural instability. We will develop smart approaches to protect them from decomposition using conductive layers and moreover design and optimise the reactors and reaction conditions that favour their photocatalytic activity as well as their preservation. This way halide perovskites will become a new front-runner in the field of photocatalysis, ensuring important advances towards a more sustainable mix of clean energy and feedstocks for current and future generations.

4. **EP/R041822/1, Bioinspired green manufacturing of next generation energy storage materials, Patwardhan.**

The ubiquity of lithium-ion batteries (LIBs) in portable electronic devices have led to an enormous volume of research on materials promising improved performance characteristics. Whether in terms of the amount of energy they can deliver, their operating lifetime or overall cost, there are pressing demands for the development of improved functional materials. In particular, Li-Ni-Co-Mn-oxides are attractive cathode materials due to their high achievable specific capacity and good long-term performance; they are also commercialised and widely used in the battery market. However, their synthesis typically requires extreme temperatures over long duration, contributing the vast majority of the energy costs. Furthermore, their manufacture is wasteful and is unsustainable. Hence the use of more sustainable synthesis routes has the potential to drastically reduce this expense.

Learning from biology, we aim to discover new bioinspired routes to produce energy storage materials. These methods will need lower temperatures, leading to reduced energy demands, and allow for superior control of materials properties on the nanoscale. This is a radically new approach, which has never been applied to energy storage materials.

5. **EP/R041733/1, Freeform Composites: Breaking Free from the Mould, Fairclough**

When making a carbon or glass fibre composite part, a mould is required. The mould supports the flexible composite fabric and adhesive while the adhesive sets. Once the adhesive sets the mould is no longer required. These moulds are expensive to make and wear out over time. As they are expensive, designs tend to change slowly, as the cost of the mould needs to be recovered by repeated use of the mould. But, what if, you only supported a small piece of the part while it cured and then moved on to other parts. Ultimately you could draw the part in 3 dimensional space, just as a pencil draws on flat paper.

The benefit of this would be the ability to create lightweight strong parts. Unencumbered by

the restrictions of a mould, with fewer joints and therefore more resilient structures. Is this not already done with 3D printing? In essence yes and no, in 3D printing of composites, either short fibre in resin matrix are used (FDM type) or layers are cut to shape and placed on a flat bed, with successive layers added. Here the joins between the layers are weak and the flat layers are not oriented to give the strongest structures. This new system will produce optimal structures, emphasising the directional properties of carbon and glass fibre to create strong lightweight structures for bespoke engineering applications. These could find uses in new lightweight bridges, car parts, prosthetic limbs, even aircraft wings. The importance of this mould free process, is the fact that it can be easily scaled by building a larger robot. A large robot could therefore build a wing or a canoe whatever the customer required at that time. This new system would create truly flexible composite manufacturing.

Overview of Proposed Research.

The research will create low friction surfaces that will not foul with resin by using fluorinated polymer brushes lubricated by a fluorinated oil. The oil and resin are chemically incompatible and do not wet each other. This surface will be pressed into the composite fabric, deforming it into the required shape, in the same way that Two point incremental forming (TPIF) operatives on aluminium. As the fabric is deformed, the resin will be applied and the composite will be cured. In the first stage of the work by UV, for glass fibre (SMC) and thin carbon fibre panels, in the later stages by microwave curing. To create larger parts, wide carbon fibre tape (1-2cm) will be woven into mats. The ends of the tape will be fed into the system, (with new tape woven into it, as the tapes extend) creating new surface that can be subsequently cured. In this way a continuous weaving, pressing, curing process is created. This would allow for the first time the creation of freeform composite parts. In the early stages this will be limited to panel structures but the long term goal is to integrate this with 3D weaving technology.

6. **EP/R04189X/1, Ahead of the Curve: Engineering Simulation for Computers of the Future, Lind.**

Modelling and simulation is a key element of research, development and design in engineering generally; it assists in the creation and optimisation of tools and methods across industries from aerospace to manufacturing to biomedical. Despite the significant supercomputing power available today, we are still surrounded by problems of great societal and economic significance with a complexity far beyond the reach of modern computation. Examples include direct numerical simulation for turbulence on real-life scales (e.g. an entire aircraft), patient-specific digital drug trials, accurate weather prediction over months, rather than days. Emerging technologies and exascale supercomputers will greatly improve our simulation capability, and there are several EPSRC and EU funded projects addressing the challenges to simulation on these systems. In the not-to-distant future however, quantum computers promise to revolutionise the information age and, accordingly, the potential for simulating complex engineering problems. While exascale systems may calculate at a quintillion flops, quantum computers may be theoretically unlimited in clock speed, hindered instead by matters such as information transmission time. Practical quantum computers in mainstream use remain many years away, and while there is a concerted effort in hardware development (in research and industry), comparatively little attention is being paid to numerical algorithm development for engineering simulation on these new devices.

This project addresses this oversight by exploring the amenability of popular contemporary numerical algorithms to quantum computing. Algorithm comparisons will be carried out on emulated quantum systems and, if possible, algorithm enhancements suggested for a better fit to future non-deterministic architectures. A key deliverable will be the first framework for practical numerical algorithm development for quantum machines for use by engineers in modelling and simulation in the coming decades.

7. EP/R041768/1, Renaissance of alloys: nanocrystalline bimetals, Polcar.

We propose the simulation-based design of a novel class of lightweight alloys with unrivaled mechanical properties and thermal stability. Our ambition is to combine just two metals with the oldest metallurgical concept (grain boundary control of mechanical properties) to beat the most modern superalloys in their high temperature use. Unlike many existing nanostructured alloys, our solution has a remarkable feature - it eliminates grain coarsening almost up to melting point.

Recent thermodynamic analysis of nc-metal alloys indicates that minority species tend to segregate at grain boundaries, which allows a decrease of the grain boundary (GB) energy, and thus a reduction of the grain boundary mobility. Under such conditions, nc-metal alloys with a positive enthalpy of grain boundary segregation minimize the Gibbs free energy at a certain grain size, and attain a thermodynamically stable nanostructure. Recent work on binary systems has shown that thermodynamically stable nanocrystalline alloys generally require a large enthalpy of grain boundary segregation relative to enthalpy of mixing, or, otherwise, a reasonably negative grain boundary interaction energy.

To screen stability of nanocrystalline alloys, we will use recently developed thermodynamic methodologies aimed at identifying elements and relative chemical compositions allowing a nanocrystalline state to occupy a relative minimum of the Gibbs free energy. In this project, we will focus only on promising combination of lighter elements (e.g. Ti, Mg, Al, Zr, Nb). First objective is thus to identify the most promising alloy based on simulation. Then, we will prepare such alloy and test it. We will use magnetron sputtering, which allows extending the solid solubility limit and refining the grain size down to the nanometre range. A combinatorial sputtering approach (i.e. chemical gradient in horizontal axis) speeds up the evaluation of structure, thermal stability and mechanical properties. Standard pre and post-annealing structural analysis (particularly elemental distribution across grain boundaries by EDX/EELS) will be coupled with in-situ observation of doping element segregation at grain boundaries in transmission electron microscope. The latter approach sheds light on initial diffusion, which will in turn be used to improve input into simulations. Mechanical properties and creep will be evaluated by nanoindentation including in-situ high temperature testing in a protective atmosphere at temperatures up to 800C.

The main result should be identification of possible alloys by model and validation of their preparation route and functional performance.

Resilient Nation:

1. **EP/R036225/1, Carboglass: Transformative Engineering Materials for Reduced Energy and Waste Consumption in Advanced Manufacturing Processes, Bingham.**

   The overarching goal of this project is to establish the technological potential, through a proof - of - concept study, of an entirely new family of glassy materials which could safely and stably incorporate high levels of CO2 by locking it away within the structure of the material in a stable form that is resistant to air, heat and light. In doing so it is believed this will present multiple new properties and in so doing this will enable transformative industrial changes in the way we manufacture, use, recycle and think about glass. There are three main pathways to academic and commercial impact: (1) UK glass industry and community (the primary route); (2) Multiple UK manufacturing sectors, specifically electronic devices and photonics; and (3) UK nuclear industry, specifically waste immobilisation and site license companies. Carboglass could provide multiple new innovation platforms for advanced materials and manufacturing technologies; carbon capture and storage; nuclear decommissioning; and energy and CO2 emissions reduction, thereby impacting upon policy, health and quality of life; delivering the capability to disrupt existing business models and contributing towards a more resilient, productive and prosperous nation. This research could lead to new technologies that provide the UK glass industry with CO2 emissions savings of up to 50% (1.25MT/yr) and increase resource efficiency by up to 20% (1 MT/yr, saving £100M/yr). It could also provide a new path for treatment of carbon-rich radioactive wastes, and could become a leading carbon capture and storage (CCS) technology. This disruptive development could lead to new high-skilled UK jobs and offer a technology platform for uptake by other industries. The proposed research will take the form of 3 work packages (WP's) that will lead to proof-of-concept, as follows: WP1. CO2 incorporation (Months 1-20). Determine key chemical, structural and processing factors governing CO2 incorporation in materials. Materials ncorporating CO2 will be produced. Outcomes: relations mapped in model systems, boundaries defined. WP2. Composition / structure / property relations (Months 3-24). Map relations in model materials with focus on CO2 incorporation and physical / chemical properties. Outcomes: fundamental understanding of effects of CO2 incorporation on material properties and structure achieved. WP3. Carboglass technology development (Months 12-24). Build / disseminate understanding of research needs to enable development of Carboglass technology towards high volume manufacturing. Outcomes: clear understanding of research needs for development of Carboglass technology, with initial upscaling designs disseminated widely to academic and industrial partners. Public benefits of this research will include improved environment and quality of life (lower CO2 emissions and energy use; safer nuclear waste, new functional materials leading to new products and processes); disruption of business models (UK jobs and wealth creation); and raised public interest in science and technology. Carboglass represents an opportunity for the UK to lead the world in new, clean and green technologies and simultaneously provides multiple new pathways for a resilient, productive and healthy UK.

2. **EP/R041903/1, Biopolymer treatment for stabilisation of transport infrastructure slopes, Hughes.**

Slope failures (landslides) cause significant disruption to our transport network. In 2015 143 failures like these were recorded on the rail network alone. In addition to causing frustrating delays these failures also cost a significant amount to repair. Failures usually occur during winter months as a result of high rainfall but this is just the end point of a process which may have been occurring for several years. Long exposure to the UK's changing weather causes the compacted clay soil which forms the embankments that our highways and railways are built upon to weaken over time. Very fine cracks develop as the soil is repeatedly dried out and then re-wetted by periods of dry and then wet weather. This effects the way water moves through the soil, the cracks allow water to get deep into the slope very quickly and large pressures can build up, pushing soil particles apart. Ordinarily, during hot dry weather the opposite happens. Water is taken out of the soil by the action of evaporation and transpiration of plants, this induces negative pressures which force soil particles together, strengthening the slope. These negative pressures build up during the summer and help keep the slopes stable during the winter. The capability of soils to generate these negative pressures is reduced by the formation of cracks. A combination of these factors can weaken the soil to such a point where one large rainfall event can cause a slope to de-stabilise.

This project will develop a new way of strengthening soil slopes and preventing these types of failure from occurring. Biopolymers, naturally occurring polymers formed by the action of microorganisms, can be added to soil to improve its strength and reduce the potential for cracking. The biopolymers mix with water in the soil to form gels which bind with soil particles giving the soil greater strength and reducing permeability. Biopolymers are already utilised in cosmetics and food as thickening agents so they are relatively cheap. They also do not require significant amounts of energy to produce and therefore they are not associated with high carbon dioxide emissions like other potential soil binders (e.g. cement and lime). Whilst the potential of biopolymers has previously been identified they have not been applied to slope stability problems and the way they form bonds and fill soil pores has not been studied fully. This project will carry out a detailed investigation of how biopolymers interact with compacted soils and use the information gathered to develop a new binder suitable for use in the repair and maintenance of highway and railway embankments.

3. **EP/R036705/1, Tackling AMR in Wastewater Systems with Sneaky Bacteria, Graham.**

Domestic wastewater treatment is among the main reasons why community health has improved dramatically since Victorian Times. Waste treatment plants (WTPs) effectively remove pathogens, carbon, and nitrogen, creating a healthier environment and reducing the waterborne infectious disease. However, WTPs were never designed to remove contemporary contaminants, such as antimicrobial resistant bacteria (ARB) or genes (ARG). Current WTPs reduce many ARBs/ARGs from wastes, but the "worst" sub-fraction of ARGs increase in WTPs, especially multi-ARGs (MRGs) that create the potential for indestructible pathogens. Researchers have been studying why multidrug resistance (MDR) is selected in WTPs. However, the cause is unknown, which impacts the long-term resilience of our water infrastructure.

In the 1950s, German researchers observed a strange bacterial form in activated sludge (AS)

in WTPs, called L-form bacteria. L-forms are "normal" bacteria that temporarily lose their cell wall. Although interesting, this observation was not pursued further. However, medical researchers recently discovered that L-form bacteria are common in MDR urinary tract (u-tract) infections, and my speculation is that L-form bacteria, which are intrinsically MDR, might be the "unknown" cause of MDR in WTP effluents. To test this bright idea, ~40 samples were collected from two UK WTPs and very high levels of L-form strains were found, especially in AS floc. Further, all L-form strains were putative "gut" bacteria, implying MDR in WTP effluents may be due to the selective survival of gut-originated L-form bacteria that "hide" in floc (in pseudo-dormant state) and then "sneak" back into WTP effluents because they survive waste treatment in their L-form state.

The project do the following:

- Develop better methods for detecting L-forms in wastewater;

- Quantify environmental conditions in WTPs where L-form bacteria are selected and hide, and determine what triggers their reactivation;

- Identify gene expression targets that promote/repress the L-form state and identify specific locations in WTPs where L-forms can be selectively destroyed; and

- Perform bench- and pilot-scale reactor work to develop new treatment strategies to reduce MDR, especially aimed at reducing L-form survival in WTPs effluents.

We already have >700 microbial MDR isolates from WTPs in the UK, Spain and India, although few have been tested for L-form development. However, early data suggest L-forms are common in AS, consistent with German observations. Within this context, work initially will focus on characterising our current MDR isolates in detail, especially categorising strains prone to L-formation and also identifying the presence and absence of key "L-form trigger genes" (in our isolates). Target genes will be refined and tested for diagnostics of L-forms, and also how their prevalence and local environments relate to MDR indictors (using qPCR, NGS and resistomics). With these data, structured sampling will be performed with three industrial partners on eight full-scale WTPs with different biological treatment technologies to identify "hot spots" of L-form selection and survival. Locale data will be used to guide lab- and pilot-scale testing of new and retrofit technologies to reduce MDR levels in WTP effluents, which will inform strategies for increasing resilience in our urban water infrastructure, especially reducing AMR spread and protecting community health.

This proposal will deliver key outcomes for A Healthy and Resilient Nation, specifically H2, H3, R2 and R3, because it will generate basic and practical data that impacts all WTP designs in future; designs to reduce MRGs released to the environment. Beyond this outcome, transcendent discoveries will be made on the genetics, ecology and selection of L-form strains, which will inform the medical community on MDR infections and also improve diagnostics in both clinical and environmental settings.

4. **EP/R041644/1, Harnessing free energy - the microbial way, Dolfing.**

There is an urgent need to make the water industry more sustainable. Currently water companies consume 3% of all electricity produced in the UK. Half of this energy is used for aeration of the activated sludge systems that have served the industry for a century, but are no longer deemed sustainable. Modern bioelectrochemical methods hold great promise as alternative, more sustainable wastewater treatment methods. Avoiding the energy intensive and expensive aeration step these technologies use the internal chemical energy present in the wastewater to produce electricity or biofuels such as hydrogen gas. However, the current generation of bioelectrochemical systems is still in its infancy; the energy recovery of these systems is notoriously inefficient.

My bright IDEA is that a thermodynamic analysis of the various steps inherent to microbial electrolysis and microbial fuel cells has unexpectedly and counterintuitively revealed that the reactions at the anode of these systems are exergonic yet endothermic. This has apparently never been calculated before, but opens up the vista to harvest the energy/heat flow associated with the anodic reaction. The microbial processes occurring at the anode take up heat. The aim of the proposed research is to confirm experimentally that this flow is as significantly as my calculations predict, and then develop a method to harvest this energy. The IDEA is to use thermoelectric materials, semiconductor solids that produce electric current when joined together and subjected to temperature differences across the junction. The concept is not just "bright", the technology that it will spurn has the potential for a step change in the water industry and beyond. In the water industry it may/will be the breakthrough that ushers in a new era of energy efficient bioelectrochemical wastewater treatment methods. Beyond, the concept will open up similar opportunities in other branches of green biotechnology. And further afield, in the chemical industry, the concept to harvest energy from exergonic yet endothermic process steps will have analogous applications. The bright IDEA research proposed here aims to provide the proof of principle for these developments. We will protect the iIDEA with a patent.

5. **EP/R041504/1, Development of a Novel Self-Healing Composite for Sustainable and Resilient Concrete Infrastructure, Zhang.**

Concrete is the most widely used construction material in the world. The construction industry annually uses 4.3 billion tons of ordinary Portland cement (OPC) as binder for concrete, accounting for around 7% of global CO2 emissions. To reduce the environmental impact of concrete industry in the UK, industrial by-products, such as pulverised fuel ash (PFA) and ground granulated blast-furnace slag (GGBS), are usually used for partial replacement of OPC. Although partial replacement of OPC can reach up to 50%, the total replacement of OPC in concrete with these wastes is not feasible without the addition of alkaline activating agents.

Geopolymers, also called "alkali-activated materials", that are cement-free eco-friendly materials synthesized at ambient or elevated temperature by alkali activation of aluminosilicate source materials such as low-calcium PFA and GGBS, have been drawing a lot of attention as a promising alternative to OPC. GPC has many advantages over OPC concrete (OPCC), such as light weight, good fire resistance, low alkali-aggregate expansion, and good resistance to corrosion, acid attack and freeze-thaw cycles. Using geopolymer as the binder in concrete can help reduce embodied energy and carbon footprint by up to 80%. However, GPC is inherently brittle similar to OPCC and susceptible to cracking that would facilitate

corrosion of reinforcing steel and impair durability of reinforced concrete (RC) structures, and thus hinder its widespread application. In addition, the resilience of concrete infrastructure that associates with the usability of RC structures is a major concern. It is essential for GPC to possess the capability to recover permanent deformation upon yielding (i.e., re-centring) or the ability to reduce residual crack sizes (i.e., crack closure) when subjected to cyclic loads in order to maintain the functionality and serviceability of a structure over its service life. As such, it is vital to develop strain hardening fibre reinforced GPC, also known as engineered geopolymer composite (EGC) to suppress the brittleness of GPC and improve its durability through multiple crack propagation with controlled crack widths.

In this project, for the first time, a novel self-healing EGC that integrates the greenness potential of GPC and the energy absorption capacity of shape memory alloy (SMA) fibres without permanent deformation will be developed. The project involves the development of a novel mix design methodology that integrates micromechanical modelling, design of experiment and life cycle analysis. A range of advanced experimental techniques (e.g., in-situ X-ray computed tomography imaging, image volume correlation, and scanning electron microscope) and modelling approaches (e.g., multiscale lattice Boltzmann-finite element method, and multiscale fracture model) will be used to characterise microstructure and simulate engineering properties of EGC respectively, which will provide insight into the overall performance of EGC and its self-healing efficiency.

This research will make it possible to develop a novel EGC with eminent mechanical properties and desired crack-healing capacity. It would expedite the use of GPC and SMA fibres in civil infrastructure applications, particularly for concrete structures subjected to dynamic loads and aggressive environments, which will help greatly enhance resilience, sustainability and durability of concrete infrastructure. The outcomes of this project are expected to result in direct benefits to society by extending the lifetime and by reducing the environmental impact, and repair and maintenance costs of RC structures.

6. **EP/R039178/1, SPINE: Resilience-Based Design of Biologically Inspired Columns for Next-Generation Accelerated Bridge Construction, Kashani.**

A resilience-based design approach plays an important role in the design of new bridges and other structures. The structural elements of bridges are often directly exposed to the environment without any protection. Even though life-cycle and sustainability criteria have been incorporated in new design guidelines, there is still no design and construction technique that can fully address the future demands of a resilient and sustainable transport infrastructure.

The aim of this research is to produce innovative and transformative engineering solutions for a durable, low-maintenance, low-cost, and demountable accelerated bridge construction technique, which is resilient to environmental threats, and natural hazards. The solutions will include a completely new resilience-based bridge design approach and biologically inspired composite columns for next-generation accelerated bridge construction.

Towards this goal, this research will construct an innovative composite bridge column, which is inspired by the mechanics of the human spine. In the human spine, intervertebral discs

provide flexibility, dissipate energy from the movements of the human body, and absorb and transmit forces without damaging the vertebrae bones. The proposed spinal bridge column will be constructed using precast composite segments (the 'vertebrae'). A new smart composite material will be developed and used in between of these solid composite segments (the 'intervertebral discs'). This will keep the vertebrae from rubbing against each other, transfer the shear forces through friction, absorb the impact due to the rocking of vertebrae, and provide mechanical damping under dynamic loading. Finally, the vertebrae and intervertebral discs will be tied together using an unbonded composite post-tensioning tendon (the 'longitudinal ligament'), to provide self-centring mechanism in the column when subjected to lateral force.

In this 24 moths research, the underlying science of the new spinal column will be investigated through experimental testing and numerical modelling. During the entire duration of the project a series of review meetings, short visits to academics as well as industry partners, and an international workshop will be organised. This interaction is deemed vital for the co-development of new concepts, the transfer of know-how and the resilient and sustainable accelerated bridge construction.

7. **EP/R041806/1, PLAIN-GG: Phase-Locked Atomic INterferometers for Gravity Gradiometry, Himsworth.**

The force of gravity across the earth is not uniform, nor constant. Any variation in mass density acts to slightly alter the local force of gravity and can provide us with a unique opportunity for detecting features which are hidden from view. Gravity gradiometry is a technique for measuring the difference in the acceleration due to gravity between two points separated by a fixed baseline. This technique has been in use for several decades for identifying underground oil and gas reserves, monitoring ocean circulation, detecting geological faults, as well as measuring the shape of the earth's gravitational field, which is necessary for accurate navigation. Current gravity gradiometers are large, heavy and complex devices typically mounted on specialised survey aeroplanes, or even on satellites (GOCE mission), and so are confined to projects with very high investment. We envision a future in which gravity gradiometers will become a more common and widespread sensor. Civil engineering will benefit the most, enabling the discovery of utilities without exploratory digging (reducing roadworks), help identify unstable areas due to unrecorded mineshafts and sinkholes, or complement general surveys for assessing ground stability. One may also envision applications in archaeology and deep sea exploration. To achieve this goal, highly compact gradiometers which still obtain very high sensitivities are needed, all within an economic package.

A recent development in the field of quantum technology will provide a significant jump toward this goal. A gravity gradiometer, fundamentally, consists of two test masses which are allowed to fall under gravity and any differences between their paths provides a measurement of gravitational variance. The key to increasing sensitivity is to remove all other forces (such as platform motion) which can overwhelm the extremely small gravitational forces, and also ensure the test masses are absolutely identical. Single atoms held within ultra-high vacuum provide, arguably, ideal test masses as they are always identical and are not subject to wear and tear. One must also ensure each atom's drop is measured using identical 'rulers'. This is achieved with a single laser beam illuminating both

atoms, as well as methods from atom interferometry - which provides atomic clocks with their astonishing accuracy - to measure the atom's path via the interference of atomic wavefunctions.

To achieve the necessary sensitivity for civil engineering applications the atoms must be separated by baseline of a metre or so. This involves a large ultra-high vacuum chamber, high power vacuum pumps, multiple optics, expensive magnetic shielding as well as several laser systems. Such gradiometers are likely to have the same bulky limitations as their more 'classical' predecessors, albeit with the potential for improved sensitivity. We aim to overcome this hurdle by exploring methods to separate the two atomic test masses and couple them via actively stabilized optical fibres. The key aspect of atomic gravity gradiometers is that both atoms experience an identical laser 'ruler'. We will achieve this by placing each atomic test mass in the arms of an optical interferometer which is controlled such that the optical field at one atom is reproduced exactly at the other. Such methods are commonly employed to transfer optical phase across hundreds of kilometres to distributing atomic clock time and are behind the sensitivity of the LIGO gravity wave detector. By adopting this method we can significantly reduce the size, weight and power of the sensor, as well as providing a variable baseline to adjust resolution (to switch between sensing deeper, larger, objects to shallower, smaller, features), and also allow multiple corrolated accelerometers to provide gradients along many different axes or position. Our goal is to engineer a robust, scalable, and practical architecture for practical applications.