Institution: Liverpool John Moores University

Unit of Assessment: UoA 12 Engineering

1. Unit context and structure, research and impact strategy

Unit context and structure

New research management structures have been developed, based around well-embedded Research Centres/Institutes (RCs/RIs) over the assessment period. Research activity in UoA 12 has been conducted through four research strands: **GERI** (General Engineering Research Institute), **LOOM** (Liverpool Logistics, Offshore and Marine Research Institute), **MEMARC** (Mechanical Engineering and Materials Research Centre), and **RCEEE** (Research Centre for Electrical and Electronic Engineering). These are based within LJMU's Faculty of Engineering and Technology from which UoAs 9, 11 and 13 are also returned in REF 2021. In this submission, 48 Category A staff members are returned, 10 of whom are from GERI, 16 from LOOM, 10 from MEMARC, and 12 from RCEEE. 15 of those returned were appointed as ECRs.

In 2014, the Faculty undertook a strategic review with the aim of achieving sustainable research in engineering and technology. The Unit's strategy has been to focus on core research areas with established research groups and support new academics through targeted financial support of both PDRAs and PhD studentships (internal research funding of £2.5m from the Faculty has been invested over the assessment period). Overall, the research in this Unit has achieved the target set over the 2014-20 period in terms of research publications, a vibrant research environment and academic and industrial impact. The number of FTEs returned in REF2021 has increased to 47.2 from 31 in REF2014. The research publications produced over the assessment period include 650 SCI-cited journal papers (150% increase compared to the previous REF period), 100 other journal papers, 300 conference papers, 30 invited book chapters, and 10 research monographs. Over the assessment period, the returned members have generated £15m of external income (£8.83m spent), supported 95 PhD completions, managed 50 PDRAs, and achieved a substantial level of international visibility. The returned members have also achieved significant impact in industrial sectors through the application of their research.

The Unit's vision is to deliver fundamental and applied research within its core areas that make significant contributions to the knowledge base, and leads directly to a beneficial or positive influence on the economy, society, public policy or services, culture, the environment or quality of life.

The Unit's **research and impact strategy** over the assessment period was to:

- Target expertise at technological applications addressing distinct regional/national/global challenges, government priority areas and societal need, focusing on its core research areas of Advanced Materials and Manufacture, Maritime Technologies, Electric Drives, Microelectronics, and Energy and Sustainability.
- Establish research partnerships with both the academic community and industrial sectors.
- Develop and deliver single, multi- and inter-disciplinary research projects.
- Increase capability in core research areas through both internal and external support.
- Invest in high quality research infrastructure and equipment.
- Increase the PGR population in key research and application areas.
- Develop/increase knowledge transfer to end users.

Evidence of the delivery of the overarching strategy is shown below by activity within each of the four research strands.

GERI – GERI comprises 3 professors, 1 reader and 6 lecturers/senior lecturers (2 ECRs), and is led by Harvey. GERI is a world-class centre for research in the fields of manufacturing and measurement technology. It can trace its history back over 40 years with an international reputation in research in areas of advanced manufacturing and optical metrology. It offers a unique skills and knowledge portfolio that links these two areas and this enables it to tackle challenging interdisciplinary research problems. Over the assessment period, GERI has

benefited from infrastructure and capital investment of over £2m. GERI's research focuses on: 1) high speed optical metrology, 2) new fusions of microscopy techniques, 3) laser micro-machining, 4) laser surface processing, 5) functional surfaces, 6) high efficiency grinding technology, and 7) advanced manufacturing with particular reference to problems that arise in industrial practice. GERI has coordinated a H2020 project *DigiArt* (Burton as coordinator, €2.35m, 2015-19) and a number of externally funded projects (*e.g.* EP/N022998/1, £330k, 2016-19) over the assessment period.

LOOM – LOOM is led by Wang and comprises 3 professors, 2 readers and 11 lecturers/ senior lecturers (7 ECRs). A distinctive strength of LOOM's research is the security and risk-based design/operation of large ships, offshore installations, port systems, maritime logistics and air/rail operations. More recently, LOOM has developed two new research interests from the appointment of 3 ECRs. One area is offshore renewable energy (EU-funded *ARCWIND*, €400k, Bashir) and the other is aircraft modelling, drone technologies and real-time simulation (EP/P030009/1, £365k, 2018-22 & EU Clean Sky 2 award/831969, €180k out of €3m allocated to the Unit, 2019-21, Lu). The support and funding from industry, government agencies, charitable organisations, EPSRC, EU and internal sources have enabled the development of a number of highly novel and flexible assessment tools to facilitate the design and operation of large maritime and other transport systems. Over the assessment period, LOOM has coordinated 4 EU-funded research training networks supported by €4m of funding, and participated in another 9 EU-funded projects with a total funding of €3m to the Unit.

MEMARC - MEMARC is led by X. Ren and I. Jones. 11 MEMARC researchers include 2 professors, 1 reader and 7 lecturers/senior lecturers (4 ECRs). MEMARC conducts research into fracture and contact mechanics, wave propagation in lattices and microstructures, thermal fatigue and thermal striping, finite element modelling and design, fluid dynamics, materials development and processing, and dynamics and autonomous systems. The research work has covered areas relevant to a number of key industrial sectors (*e.g.* energy and nuclear) and emerging multi-disciplinary research areas (*e.g.* sport technology and health care). The research work in the mechanics of engineering and biological materials has been supported by investment in a modern materials and structural testing laboratory. It has also been supported by 1 EU-funded research network, 2 incoming fellowships (coordinated by X. Ren), the Nuclear Security Network and industrial sources (*e.g.* International Nuclear Services). MEMARC's research has been enhanced by the appointment of 3 ECRs in two emerging research areas. One area is additive manufacturing/3D printing of metals and understanding the links between manufacturing and material properties, with funding from the US Air Force Office of Scientific Research (£150k, 2018-20, Tammas-Williams). Another area is the modelling of turbulent flows in renewable energy generation (EP/S037292/1, £260k, 2020-23, Seddighi).

RCEEE – RCEEE is led by Levi and J. Zhang and includes 4 professors, 3 readers and 5 lecturers/senior lecturers (2 ECRs). RCEEE has achieved a substantial international reputation and played a significant role in the international arena in the areas of "Multiphase and multi-motor drive systems" (Electric Machines and Drives) and "Qualification of VLSI devices and materials" (Microelectronics) during the REF period. The research in electric machines and drives focuses on innovative research topics related to multiphase electric power generation and power electronics for electric vehicles. The research in Microelectronics focuses on three key issues of IoT and AI (power, cost, and security) through joint projects with world-leading organisations such as IMEC, ARM, and Synopsys. One indicator of RCEEE's achievements is the large number of research papers published in IEEE Transactions (over 70) and at the flagship conferences - IEDM/Symposium of VLSI Technology (15) - since 2014. RCEEE's research has been supported by a number of external funding sources including EPSRC (*e.g.* EP/S000259/1, £378k; EP/M006727/1, £350k; EP/L010607/1, £518k; EP/I012966/1, £463k; EP/I038543/1, £200k; EP/T026022/1, £487k awarded to J. Zhang, W. Zhang and Levi) and Innovate UK (e.g. £255k, "Smart Industry 4.0 ready power controllers"; £220k, "A smart production management system" awarded to Ateeq) since 2014.

The four groups within the Unit have worked collaboratively to conduct joint research programmes of multi/inter-disciplinary research challenges while members of each research group are encouraged to develop their own individual areas of expertise, where appropriate. For example, Sharp (GERI) and Seddighi (MEMARC) have jointly won an InnovateUK grant of

£396k allocated to LJMU in collaboration with Sandon Global Engraving Technology Ltd (2019-21). Collaboration between researchers within the Faculty and across faculties is actively encouraged (*e.g.* through joint PhD studentships and grant applications). For instance, ship simulator-based research in the Unit has collaborated closely with the psychophysiology group (Fairclough) in the Faculty of Science, with 3 jointly-supervised PGRs investigating how human error can be estimated and reduced.

There have been significant increases in research income, staff and PhD students and investment in research infrastructure and equipment. As some of the Faculty's most senior Experienced Researchers, with the knowledge, experience and foresight to drive the Unit's research and impact strategies, the named RC/RI Leads (pp 1-2) represent their respective research groups on the Faculty Research and Knowledge Exchange Committee (FRKEC), which convenes every 2 months and is chaired by the Faculty Associate Dean – Research (ADR). The ADR (Wang) is a Faculty Management Team member and the Faculty representative of the University Research and Knowledge Exchange Committee (URKEC).

New research collaborations at regional, national and international levels in line with the Unit's research and impact generation policy have resulted in a more vibrant research environment. Interdisciplinary synergies with other groups at LJMU have been actively exploited. For example, maritime safety research has been linked to cyber security research in Computer Science and Mathematics to improve safety in ship design and operation; and materials engineering researchers have collaborated with the Research Institute for Sport and Exercise Sciences to enhance athletes' performance. The relevance and value of the Unit's interdisciplinary research approach is evidenced by the coordination of 7 EU FP7/H2020 projects and hosting of 1 ERC research grant, and also by the establishment of a £5m Materials and Manufacturing Research Base between LJMU's Physics, Engineering, Computer Science and Sports Science disciplines.

Strategic plan and goals for research and impact

In line with the University's research and knowledge exchange strategy, the Unit has built upon the successes achieved, using the research management structures and capabilities that have been developed in the Unit to focus on providing innovative applied engineering and technology solutions to national and global challenges. The Unit has developed its infrastructure and knowledge base to provide researchers with an environment in which to maximise the impact of research, and to enhance the sustainability and vitality of research. The Unit's **strategic research and impact plan** has eight key objectives:

- Engage with government, industry and academic partners to identify and address key national and international research challenges.
- Develop single-, multi- and inter-disciplinary research programmes in a range of engineering applications.
- Attract internationally-leading research talents and develop key engineering research areas through growth in the number of academic staff, contract researchers and PhD students.
- Provide research leadership and a diverse environment that supports researcher career development, recognizes achievement and rewards success.
- Invest in and maintain a high-quality physical environment that provides researchers with the facilities and equipment required to support ambitious research programmes.
- Operate a sustainable business model to support research activities.
- Enable rapid transfer of research outcomes to business, the economy and society for impact generation.
- Contribute to public awareness of engineering and technology research.

New and/or extended collaboration has been developed with regional high-profile innovation initiatives (see pp14-15 'Interdisciplinary and collaborative research'), particularly in the sectors of Renewable Energy, Safety and Sustainability, Health and Manufacture, Mechanics and Materials, Transportation, Electric Drives, and Micro-electronics. The Unit has created new groups of excellence in key research areas (*e.g.* autonomous systems

research) to train the next generation of research leaders and to promote knowledge exchange. The Unit's PGR community has increased through an expansion of industry co-funded studentships and by establishing three new dual PhD programmes with leading overseas institutions (*e.g.* the University of Malaya). This has been aided by Faculty-wide Research Seminars, the Unit's monthly Research Presentations, and the annual Faculty Research Week where industrial users and internal researchers are regularly invited for collaboration and impact generation. The Unit has benefited from investment in new/upgraded equipment/infrastructure, including a Ship Operations laboratory, and the £5m redevelopment of the James Parsons campus where all four engineering Research Centres/Institutes in this Unit are housed.

Knowledge exchange, impact generation and staff support

Significant effort has been invested in transferring the Unit's research knowledge to industry. The Unit formalised its impact strategy in 2014, building on its experience of active knowledge transfer to industry over the past two decades. The Unit has continually encouraged all members to be actively involved in impact-generating activities. Strategy objectives achieved over the assessment period include: 1) the engagement of industrial partners in the Unit's research activities, 2) supporting financial impact-generating activities for knowledge exchange, 3) building partnerships through academic secondments to industry and hosting industry specialists in the Unit, and 4) prioritising areas for knowledge exchange. Jenkinson**,** the **first Professor of Enterprise** appointed at LJMU, has led such knowledge exchange activities with other members actively involved in the Unit. Each year, five or more of the Unit's members have been, and continue to be supported, either by internal or external funds for industrial secondments of one to six months for impact-generating purposes, with more details provided in Sections 2 and 4.

The Unit utilises a list of industrial organisations to prioritise collaboration that leverages the greatest impact. This list has been updated on an annual basis with each organisation having a designated contact. Although the majority of such organisations are local or within the UK, the international element is integrated into the research projects' impact-generating plans. For example, maritime safety-related impact-generating activities have been and continue to be conducted internationally with industrial organisations (*e.g.* COSCO and China Shipping Group) because on-going collaboration and ship operational activities largely take place in the Far East.

The types of impact delivered to and through these industry collaborators have included:

- Economic impact: Innovative industrial processes and products; increased productivity, turnover and employment; and reduced industry waste and costs.
- Environmental impact: Efficient utilisation of energy sources.
- Quality of life impact: Contribution to public policy; public safety; improved health products; and improvement of transport efficiency and safety.

The research has had a direct quantifiable impact on regulatory and public policy, and the practices and activities of industrial organisations and services. The following exemplifies knowledge exchange, impact generation and staff support:

- A systematic decision-support methodology, together with a series of associated sector-specific models, has influenced industrial practice by shaping a goal-setting regime for maritime systems operations. The range of organisations influenced by the research has included regulatory and classification bodies (*e.g.* HSE), maritime operators (*e.g.* Shell) and consulting companies (Risktec), in the UK and internationally. The research, supported by external grants (£2m from EU, RCUK, industry and HSE) and internal grants (*i.e.* LJMU's pump priming fund of £200k to Loughney) has led to the development of HSE guidance on avoiding offshore installation-ship collisions and improving the current capabilities of equipment able to warn of a potential collision. 184 offshore oil and gas platforms on the UKCS and 1,327 worldwide have benefited from these guidelines since 2019 (REF3-ICS1).
- Based on commercial instruments, the micro-electronic research team developed a number of advanced characterisation techniques that require technique-specific programs and hardware setups. The research outcomes have been used by Tektronix, embedding them into their semiconductor parameter analyser. Up to September 2019, 3,145 such analysers had been shipped together with the instrument to world-wide customers. The industry has

formed a consortium, based at IMEC, Belgium, whose members include Intel (US), ARM (UK), Samsung (Korea) and Toshiba (Japan). Each company has its own assignees based at IMEC. The micro-electronic team had one researcher based at IMEC (50% funded by the University), who took part in the daily R&D activities of the consortium from 2016 to 2019. This offered a direct bridge between the Unit's micro-electronic research team and the consortium. The Unit's research has impacted the development work in terms of material selection, structure evaluation, and performance optimization (REF3-ICS2).

- Transportation/logistics research has been supported extensively by industry-academia funding (including DfT and InnovateUK), as well as funding from the EPSRC, EU, Newton Fund and various charities (£5m in grant value to LJMU in total). The resulting decision-aiding tool (Nguyen and Yang) has led to greener, more efficient and more sustainable transport and logistics since 2017: 1) Reduced costs (up to 23%) and emissions (up to 19%) in the Ports of Liverpool; 2) Improved rail performance and passenger experience (helping Merseyrail to monitor four of its busiest stations (24 million passengers annually)); and 3) Supporting active travel options (walking and cycling) in the Liverpool City Region (LCR) by providing data/analysis to both users and local authority operators to reduce GHG emissions (REF3-ICS3).
- The research on abrasive mass finishing (MF) is industry-focussed, inherently cross-sectoral and multi-disciplinary (Batako, Chen and Morgan). The research attracted a number of significant external grants (£1.5m from InnovateUK and industry). The knowledge transfer has led to impacts including: 1) A £2.5m factory built in the UK for high-volume production of the product, with improved production efficiencies; 2) A wider product offering as well as increased sales revenue, with a value of £1.2m in the first two years of production (2017-19); and 3) A method of finishing that is cleaner and more environmentally sensitive than any other available process technology, with a cost saving of 40%. Landis-Lund has used the developed High Efficiency Deep Grinding (HEDG) technology in its twin crankshaft grinders worldwide since 2013, with the grinding cycle time reduced by 50% (REF3-ICS4).

The Unit's **research and impact strategy** for the next REF cycle is to broaden its collaborative culture for excellent impactful research; to extend its critical mass for enhanced research productivity and capability to tackle complex multi/inter-disciplinary research issues; and to foster research agility to embrace emerging research challenges and impact opportunities within its expertise areas. More specifically, the Unit will continue its research and impact approaches to develop fundamental solutions and integrate these into impactful applications. In particular, the Unit will invest more research efforts in the areas of green and intelligent transport, dynamic and autonomous systems, renewable energy generation, microelectronics and IoT security, manufacturing and measurement technology, and big data analytics in engineering applications.

Open research environment and research integrity culture

The University supports open access (OA) publication to make research available to the widest possible audience. Since May 2015, the Faculty Research and Knowledge Exchange Committee (FRKEC) has consistently promoted the requirement that all Faculty research-active staff adhere to this process. The research outputs produced by the Unit over the assessment period have been OA-compliant and deposited through the University's institutional repository. There is a Faculty SharePoint for the deposition, sharing and reproducibility of the Unit's research data, with internal and external users having different levels of access. The University also has a data repository to ensure that the Unit is compliant with the UKRI Concordat on Open Research Data. Moreover, projects typically create their own websites (*e.g.* DigiArt) to disseminate research findings (*e.g.* through project reports for open access, and sharing unrestricted data to encourage further research).

A research integrity culture is fostered by the University Code of Practice for Research (last updated 2020/next review 2021) and promoted in new staff and PGR inductions. The Unit has a rigorous procedure in place for external grant applications, which have to be reviewed by two experienced researchers internally before submission. General guidance on good practice in research and specific guidelines for studies involving human participants, human material or personal data and animals is promoted widely. The University Research Ethics Committee (REC) implements governance arrangements to oversee the conduct of the Faculty's REC. The

Faculty-based REC provides oversight, guidance and advice on the ethical implications of research proposals. Electronic records of all ethics applications are lodged in the Faculty's SharePoint. Zero allegations of research misconduct have been registered in the Unit during the assessment period.

Section 2 - People

Staff strategy

Staff recruitment and retention are at the heart of the Unit's research strategy. This is achieved specifically through the recruitment of internationally excellent researchers and provision of an excellent working environment that supports researchers' career development, recognises achievement, and rewards success. Nineteen of the academic staff returned in the Unit (around 40% of the returned staff) have been recruited into the core research areas since REF2014. Fifteen of them are early career researchers (ECRs); fourteen were recruited from universities in Denmark, Korea and UK while one was appointed from industry. New academic staff appointments were supported by start-up packages to fund PhD studentships and appropriate equipment purchases, as well as providing upskilling and pump priming funding. Also provided are competitive University scholarships and Faculty scholarships, with priority given to new staff and ECRs in core research areas (typically 10 to the Unit each year).

The demographic profile of the Unit is such that over 80% of the current staff members are expected to be returned in the next REF, facilitating current and future management to secure the sustainability of the Unit.

Staff Development within the Unit is a key aspect of creating a vital working environment that allows researchers to fully realise their potential. The Unit provides a wide range of mechanisms to both support and develop staff engaged in research throughout their careers. The Unit engages in a comprehensive range of opportunities for all researchers (including PGRs) to develop their personal, professional and career management skills through the University's award-winning ACTivator programme. The regular courses offered include "Building Blocks of Impact", "Ready Steady Publish", "Collaboration that Counts", and "Pitch Perfect". Online bookable services are also available for all researchers. For PGRs and PDRAs, there are further Researcher Development training courses offered on a quarterly basis, including "Researchers: Introduction to Your Support Network", and "Women Researcher Retreat". There were around 200 attendances to the courses by the UoA staff between 2016 and 2020. At Faculty level, experience-sharing workshops were organised 3 or 4 times a year where experienced staff share their good practice and lessons learnt with other staff in terms of successful grant applications to funding bodies. The Concordat has operated a robust action plan delivered through a Concordat Task Group and overseen by the URKEC. The performance of the staff development programme was recognised by the EU HR Excellence in Research Award in 2012 that was successfully retained following biennial reviews in 2014, 2016 and 2018.

Research staff joining the Unit participate in a formal induction process of preparation for their job role, providing them with the opportunity to learn about the University and their local working environment. In the Unit, each ECR has been assigned one mentor to review his/her performance, set objectives for the coming year and define a learning and development plan. Annual PDPR is monitored throughout the year and formally reviewed at the following year's meeting. This process is formalised by the FRKEC. All new staff are initially allocated reduced teaching and administrative loads to enable them to develop their research and establish personal research teams. They are given priority in the allocation of internal funding through a number of schemes such as impact generation, pump priming, equipment support and studentships. For those applying to ECR-targeted funding programmes such as EPSRC New Investigator Grants and UKRI Future Leaders Fellowships, ECRs are guided and supported by mentors, the head of the Research Centre/Institute, and Research & Innovation Services, who provide detailed advice and feedback during proposal preparation. Four of the Unit's ECRs were successful with their first grant application during the REF period (*e.g.* EP/S037292/1, £260k, 2020-23, Seddighi).

The Unit also encourages continuing career development for established staff within the Unit. Funds are allocated to support new research initiatives and develop research links with

industry partners in the core research areas. Staff are fully supported by the Unit when applying for Research Fellowships that allow them to focus solely on research and will make suitable provision to cover teaching and administration duties during these periods. One example is an ERC Consolidator Grant of €2m awarded to Yang. This 5-year award (2020-25) has allowed the researcher to develop a new research team in resilient container supply chains.

Examples of the success of the Staff Development programme in the Unit include:

- **Dordevic**: Upon completion of his PhD, he was appointed a lecturer at LJMU in 2013 and then promoted to Reader in 2018. He leads research on control of three-phase and multiphase converters. As PI, he has won an EPSRC First Grant (EP/P00914X/1, £101k, 2017-18), further competitively awarded funding from the EPSRC Challenge Network (CN/FEAS/BIPED, £121k, 2018-19), and an industry-financed project with LionSmart GmbH, Germany.
- **Lu**: He joined LJMU as a lecturer in 2017, following seven years as a research fellow at Liverpool University from 2007 to 2014 and less than two years as a lecturer at the University of Central Lancashire from 2015. He has since led a research team of four members in Aircraft Modelling and Real-time Simulation, funded both externally (EP/P030009/1, £366k, 2018-22; European Aviation Safety, *RoCS*, €180k out of €3m to Lu, 2019-22) and internally by the University and Faculty.
- **Nguyen**: After 4 years' postdoctoral research at the University of Birmingham and LJMU, he was appointed as a lecturer at LJMU in 2011 and then promoted to Reader in 2015. He is leading a research group on optimisation/simulation, data analytics, and machine learning, which focuses on maritime, transport, logistics, IoT and smart city problems. As PI, he has won external funding of £1.8m, including "*COINS*: Customer-Operational Information System for Stations" (Ref.-971641, £265k, 2018-20) and "*IRIS*: Information system for railway station staff" (Ref.-971752, £330k, 2020-21).

The University invites applications on an annual basis for conferment at Reader and Professorial levels. Over the assessment period, three of the submitted staff members were conferred with a Professorship (Yang-2014, W. Zhang-2014, Morgan-2015) and three were conferred with a Readership (Nguyen-2015, Ji-2018, Dordevic-2018). Academic staff members' teaching duties are re-allocated for sabbaticals, ranging from a few weeks to twelve months (*e.g.* Yang's industrial secondment of six months at DfT in 2018).

PGR Recruitment

The Unit has a mechanism for attracting self- or externally-funded students, particularly from overseas, including students from Brazil, China, Nigeria, and Saudi Arabia. Funding bodies include industrial and university sponsorships, the governments of China, Kuwait, Malaysia, Nigeria, Panama, Saudi Arabia and Turkey, Commonwealth Scholarship Committee and EU's Marie Curie schemes. In addition, the Unit has the following specific PGR programmes:

- Match funding for industrial PhD research. The University/Faculty offers 50% match funding (10 provided).
- Dual PhD programmes. The Faculty provides 50% match funding (6 provided).
- Faculty scholarships that support projects aligned to the Unit's strategic research areas, fundamental research, and exceptional students (30 full scholarships).
- LJMU's scholarships for exceptional students (20 full scholarships).
- Industry-funded projects. Partner companies include ABS, Babcock, BAE Systems, Bibby, HSE, Lloyd's Register, National Nuclear Laboratory Ltd., Nigerian National Petroleum Corporation, Maersk Line, NHS, Peel, QinetiQ, BMW-Munich, Ingeteam-Spain, Rolls-Royce, Serco Group and Shell (20 PGRs).

PhD vacancies are advertised in standard HE recruitment websites (*e.g.* jobs.ac.uk and FindAPhD.com). The Unit's staff also present information on PhD opportunities to students at international partner institutions. The Unit has run several programmes to encourage applications for PhD Scholarships from its own undergraduate students each year. Examples include informing final year MEng students directly through email/internal advertising of

available scholarships and encouraging participation in funded Summer Internship programmes as an introduction to research and research careers, and integrating research study modules into the core curriculum. An online application system is used to follow up applications and provide feedback to applicants. The University also runs pre-sessional English language programs for international students.

PGR Support and Monitoring

The Unit's PGR population has increased significantly during the REF period, rising from 35 FTEs enrolled in 2013-14 to 70 FTEs enrolled in 2019-20, an increase of 100%. The Unit's PhD completions have increased by 139%, from 68.5 (REF 2014) to 95 over this assessment period. The Faculty Research Degrees Committee (FRDC) Chair and PGR Coordinator (Yang) directs a range of activities and programmes (below) to ensure that these students are fully supported in their studies and career development within a vibrant PGR student culture and community.

A robust formal procedure is in place to monitor and support student progress throughout the PGR period. Each student is required to complete an annual Postgraduate Monitoring Report, in which the PhD researchers review and detail their research progress, and training and skills development; while the supervisors provide requirements/expectations for training and skill development, ethical approvals, supervisory arrangements and PGRs' position for completing their target, feedback on performance, and recommendations. The researcher and supervisors will then formulate a joint declaration before the report is passed to the FRDC for approval, which independently monitors student progress. This includes advice associated with the research process as well as guidance on training and development.

Training and secondments

All PGRs are encouraged to develop their research for presentation at national and international conferences and seminars. Student presentation skills development is facilitated by research presentation events within the research groups and participation in the more formal annual Faculty Research Week, attended by students, staff and external visitors from industry. Poster presentations for first year PGRs are required and podium presentations to highlight potential research impact are also encouraged. A panel of academics and industrialists assesses the presentations and prizes are awarded to all year groups. Each year, 3 awards are given in each of the categories of Best Potential Impact, Best Poster, Best Paper, Best Elevator Pitch and Best Oral Presentation. Each year, the Faculty's Prize comprises five awards for Best PhD Thesis. PGRs are also encouraged to enter national and international research competitions and many have been successful. Examples include the award of the GALP Datathon Data Science competition (Pieroni, €25k, 2019), the Best Paper Award at EvoApps (Yazdani, 2018), Best Paper Award at the IEEE-LISS (Alghanmi, 2017), Best Paper Award of the IEEE Industrial Electronics Society (N. Bode, 2016), Best Paper Award by the IEEE Industrial Electronics Society for a paper authored by a research student (Subotic, 2016), Association of British and Turkish Academics' Doctoral Researcher Award (Ma, 2015), and Best Paper Award at QR2MSE (Qu, 2015). PGRs are encouraged to become involved in a range of academic activities under the supervision of academic staff, including the development of teaching skills in laboratory and tutorial environments.

Through a variety of joint training arrangements and secondments in other organisations, PGRs in the Unit have gained the necessary skills for their career development in academia and/or in industry. In particular, these opportunities have helped bridge knowledge gaps between science and engineering, and between fundamental study and applied research. Exposure to different cultures and environments has also provided opportunities for ECRs and PGRs to collaborate with external researchers to experience and tackle different challenges. The Unit has co-ordinated the following UK and FP7/H2020 EU-funded training networks involving over 60 of the Unit's PGRs and ECRs:

1. EU H2020, €1,417,500, 2017-21, *RESET* - Reliability and Safety Engineering and Technology.
2. EU H2020, €1,324,800, 2019-23, *REMESH* - Research Network on Emergency Resources Supply Chain.
3. EU FP7, €384,300, 2012-16, *REFERENCE* - Risk Assessment and Decision Science.

4. UK BIS, £300,000, 2015-17, Digital innovation research in maritime logistics.
5. EU FP7, €590,000, 2013-17, *ENRICH* - EC-China Research Network for Integrated Supply Chains.
6. EU H2020, €504,000, 2019-23, *i-WELD* - Integrated Modelling of Duplex Stainless Steel.

In addition, the Unit has also participated in another 4 research networks for PhD and staff training:

1. EU H2020, €180,000 (of €517,500) to the Unit, 2017-21, *PRIGEOC* - Partnership for Research In Geopolymer Concretes.
2. EU H2020, €170,200 (out of €961,400) to the Unit, 2019-23, *ENHANCE* - Enhancing human performance in complex socio-technical systems.
3. EU H2020, €211,500 (out of €1,116,000) to the Unit, 2018-22, *GOLF* - Integration of Global and Local Agri-Food Supply Chains Towards Sustainable Food Security.
4. EU, H2020, €170,000 (out of €777,400) to the Unit, 2019-23, *REACTIVE*: Reliable Electronics for Tomorrow's Active Systems.

Forty external industry and academic partners have signed agreements for research training with the Unit, through both internal funding and external funding listed above. The partners include Politechnika Slaska (Poland), Junet Oy (Finland), Cedrat Technologies S.A. (France), National Academy of Sciences of Ukraine, Technical University of Malaysia (Malaysia), Mahidol University (Thailand), Tsinghua University (China), University of Science and Technology Beijing, and Paton Electrical Welding Institute (Ukraine). Over 40% of the Unit's PDRs and ECRs have spent one to nine months with overseas collaborators using the above external and internal funding. Examples of secondments include four months at Mahidol University for Li (LOOM) and six months at the University of Phayao (Thailand) for Tang (MEMARC). In addition, PGRs and PDRAs are encouraged to undertake industrial secondments funded by both external and internal funding. Ten PGRs and 5 PDRAs have spent from one to six months at industrial organisations (*e.g.* Sivori had a secondment of four months at Kongsberg, Norway in 2019). PGRs' career development has been integrated into such training opportunities, striking a balance between research originality and applicability. All completed PGRs have experienced a smooth transition into their subsequent career path and many of them have taken up management positions in their organisations (*e.g.* Al-Yami who graduated in 2016 is the Head of the Department of Nautical Science at King Abdul-Aziz University, Saudi Arabia).

Support for knowledge transfer and impact generation

The Unit has implemented several staff development/motivation programmes related to impact and external knowledge transfer, including:

- Training courses and mentoring in burgeoning knowledge transfer activities.
- Bi-weekly drop in sessions with Research & Innovation Services.
- Annual impact generation awards to staff (three each year).
- Targeted appointment of Visiting Professors/Researchers from industry (ten appointed including five visiting professors).
- The Faculty pump priming and impact generating fund (£100k allocated to the Unit each year).
- Ring-fenced time for industrial collaboration.

Examples of the Unit's support for impact generation

1. The Mass Finishing (MF) Abrasive Product research has been supported through a time allowance (from Feb. 2014 to Jan. 2015) to the key researchers to work with Potters-Ballotini, Glass Technology Services and Rolls-Royce (turbine blade finishing). This has led to a new factory built in the UK for high-volume production of the product. The new product has led to improved production efficiencies, a wider product offering and increased sales revenue.
2. A partnership has been formulated between Merseytravel and the Unit, brokered by the University's Knowledge Exchange team and supported by a time allowance of 6 months

from July to Dec. 2019). This has led to novel sensors and artificial intelligence techniques (developed by Nguyen's team) being used across the six local authorities of the Liverpool City Region.

3. Loughney was 50% supported by the Faculty over nine months (lecturer grade 8, from Apr. to Dec. 2018) to develop the HSE guidelines on avoiding offshore installation-ship collisions and improving the current capabilities of equipment able to warn of a potential collision. Benefits to the offshore oil and gas platforms have included cost savings from the reduced risk of the demolition/removal of damaged installations after a collision.
4. One researcher (Ji) was supported by the Faculty's pump prime funding (£40k) to undertake a two-month secondment (Oct. and Dec. 2018) at Mindray and Panasonic Semiconductor Solutions Co. Ltd., to develop a defect-based True Random Number Generator (TRNG) and its commercialization. The TRNG harvests the randomness of natural phenomena in hardware without using an algorithm, which has been used in IoT security systems, leading to a UK patent (GB2571546).

Equality and diversity

The Faculty's designated EDI Champion (Johnson) ensures Unit-level equality and diversity policies and practices are aligned with those of the University as a whole. Each member of the staff is required to complete an online training course on the issues of equality and diversity annually. Among 48 Category A staff returned to this UoA, 52% are from BAME backgrounds; 3 are women, two of whom have been appointed as lecturers since 2014 (*i.e.* Shahrokhi and Liu). All academic and research staff are eligible to access a range of family-friendly options (*e.g*. maternity, paternity and adoption leave; parental, compassionate, domestic and personal leave). They are also entitled to take sabbatical research leave (*e.g.* Yang took a sabbatical leave of three months in 2019). On average, most senior members of the Unit have each produced slightly more outputs than junior colleagues, although it is worth noting 4 ECRs (*e.g.* Tammas-Williams) have performed excellently in this aspect.

All training and support programmes are consistent with the Concordat to Support the Career Development of Researchers and respect equality and diversity. Research leadership development is fully encouraged at all career stages through collegiate and collaborative working across institutional, national and international borders.

3. Income, infrastructure and facilities

Research funding portfolio

By 2019-20, the Unit had more than trebled its annual research income to £5m, compared to 2013. The cumulative research funding for the REF period to 2020 is £15m. The Unit has co-ordinated 7 EU FP7/H2020 projects and participated in 14 EU projects (*e.g*. *INTRADE*, *WEASTFLOWS, BLUEPORT* and *EMPORIA4KT*). The current portfolio of secured external grants (over £10m) is 4 times higher than in 2013. Specifically, **GERI** has coordinated a H2020 project *DigiArt* (€2.35m, 2015-18) and led 3 InnovateUK projects. **LOOM** has coordinated 4 EU-funded research training networks (with a total funding of €4m), hosted 2 standard EPSRC grants and 1 ERC grant, and 3 InnovateUK projects. **MEMARC** has led 1 EU training network, 2 H2020 MSCA Fellowships and 2 EPSRC grants. **RCEEE** has hosted 7 EPSRC and 2 InnovateUK grants totalling £2.5m.

Investment in New Facilities and Equipment

Major investments in new facilities and existing facilities upgrades have been made since REF2014. These investments align with the vision of the Unit and with the key research areas of GERI, LOOM, MEMARC and RCEEE. They align with the strategic staffing strategy described in Section 2.

There have been partnerships with external organisations for research with the Unit. A Maritime Knowledge Hub has been formulated with an investment of £10m from Wirral Council, Peel Ports, LCR Strategic Investment Fund and the University. The research facilities include a state-of-the-art 360-degree ship-handling simulator and an engine room simulator with an additional investment of £5m. The Sensor City and Sensor Platform (a University Enterprise Zone) launched in November 2017 is backed by the Department for Business, Energy and Industrial Strategy (BEIS) and the European Regional Development Fund (ERDF). The overall investment

for this project was over £15m and provides access to the most sophisticated sensor and IoT technology. Equipment on-site includes a £250k machine that produces curved printed circuit boards – the only one of its kind in the UK in public hands. The Prototype Development Laboratory and Virtual Reality Suite also house a diverse range of state-of-the-art electronic, electrical, mechanical, optical, virtual reality and 3D printing equipment, which is available for prototype design, development and testing carried out by its in-house laboratory team. There have been 3 designated technical support staff with responsibility for maintaining these facilities. The Manufacturing Technology Centre has established its first outreach facility (over £6m investment from MTC and LJMU). It was hosted at LJMU from 2015 to 2019 but following a significant expansion of its operations it has moved to a larger facility on the Liverpool Science Park campus (close to the Unit location). The Unit's researchers have access to all equipment in the MTC facility, which includes prototype end effectors and manipulators, Stewart Platforms, adaptive and dynamic work holding, and 'Factory-in-a-Box' type process lines. Furthermore, the University has invested in the following new facilities and equipment.

***High Performance Computing (HPC)**:* In 2016, the Unit invested £250k to have two relatively small, 112-core and 244-core HPC computer clusters. Various commercial and in-house software including CHAPSim CFD, OpenFOAM, Flexsim, DNV-GL Sesam, Ansys-Fluent and Abaqus are currently run on the cluster by the researchers undertaking simulations in the areas of CFD, offshore renewables, materials, laser technologies, naval architecture, fire and smoke modelling, system dynamics, and astrophysics. In 2018, the Unit invested a further £250k to enhance the HPC facility with1000 Intel Xeon Gold (Gen10) cores @ 2.5 GHz, a RAM of 13 TB, high speed (100G) infiniband interconnect (for parallel jobs with high communication loads) and 1 PB of storage of connected storage. In 2019/2020, the Unit has further invested £450k to enhance the HPC through adding a "Tier-3" facility to facilitate diverse research computing applications and to act as a development bridge from desktop computing to the national (Tier-1) and international (Tier-0) HPC research facilities available to UK academics via Archer, DiRAC and PRACE. The facility can be used both as a "work farm", capable of running many independent computing tasks simultaneously (*e.g*. image processing), and as a massively-parallel computer capable of running individual jobs (*e.g*. fluid dynamics calculations). It comprises 1,280 AMD Rome processing cores in 20 high-density HPE Apollo compute nodes, networked with the high-bandwidth, low-latency HDR Infiniband fabric. The facility has a total memory footprint of 10TB and a long-term storage capacity of 1.5PB provided by a parallel BeeGFS filesystem.

***Human Error Assessment Laboratory**:* This laboratory has been established through £2m EU/University/Faculty funding over the assessment period. It is shared between LOOM and the Research Centre for Brain and Behaviour in the Faculty of Health. Dedicated facilities available to researchers include: EEG facilities, road simulators, ship bridge and engine room simulators, twelve experimental testing booths, a sleep-over rest room and other specialised laboratory facilities (*e.g*. motor skills). The laboratory is also equipped with a state-of-the-art functional near-infrared spectroscopy (fNIRS) device (additional investment of £200k from the Faculty) for human error studies in both road and waterborne transport. It has a capacity of high-density imaging and multi-distance tomographic recording with 32 opcodes and 48 channel recordings. 10 researchers in road, rail and marine transport risk assessment and in the design and operation of large engineering systems have regularly used this laboratory. An example of the use of such facilities is Sivori's PhD research on "Maritime simulation-based stress-induced analysis and mitigating methods while applying fNIRS" (2019-22), funded by both the University and EU (H2020 ENHANCE). Another example is Symes' research on "Simulator Based Human Error Assessment Using Functional Near Infra-red Spectroscopy", funded by the University. MarRI-UK has recently provided the lab with £200k to investigate "Lookout awareness of distractions in ship operations", 2019-22.

***Drone Research Laboratory**:* This laboratory houses "off-the-shelf" and custom in-house-built drones for a wide array of applications that range from the mapping of archaeological sites to counting orangutan populations. The laboratory has been established with the Faculty's investment of £1m and with the support of EU (H2020 DigiArt, €2.35m) and EPSRC funding (EP/T015403/1, £574k). The Drone Technologies and Sensing (DTS) research area combines some of the latest research from GERI in the field of state-of-the-art drone technology. The

research in this area has developed and worked with many optical sensing technologies, including bespoke Structured Light Fringe Projection Systems for 3D surface measurement, Interferometry and Advanced Microscopy. Areas of current drone-related research activity include: 1) new optical stereo photogrammetry techniques for precision 3D measurement from UAVs; 2) the development of LIDAR techniques in UAV operations; and 3) aerial gas sensing using drones. Facilities include a Bruker Contour GT-K 3D optical white light interference microscope, a GFM MikroCAD Premium Optical Surface Profiler, with Motorised X, Y, Z Stages, an Optonor VibroMap1000 TV Holography/ESPI System and bespoke and novel 3D Structured Light Optical Measurement Systems. The laboratory has been used by 10 researchers in the areas of conservation, drone development, forensic science, search and rescue, regulation and standards, 3D modelling and mapping and localisation. One example is Cliffe's PhD research on "Use of drones to enhance geography education fieldtrips", funded through the University scholarship scheme.

Materials Laboratory - This laboratory has been established since 2014 through the University's STEM capital investment of £5m, for research in areas of new materials development/characterization, modelling and applications with a direct link to manufacturing and product design. The main facilities include a modern materials preparation sub-lab, a material testing sub-lab (Digital Image Correlation systems and a micro/nano in situ testing system with an environment chamber), materials characterization facilities (*e.g.* X-ray diffractometry facilities and residual stress analysis), key facilities in general engineering and manufacturing and modern metrology facilities. Engineering and physics simulation software is provided, including CFD, ABAQUS, ANSYS, COMSOL Multiphysics, Thermo-Calc Software, USPEX and CASTEP codes. The materials facilities support research in new materials development (novel meta-materials, new welding materials, *etc.*), new environmentally-friendly manufacturing processes and computational materials modelling at different scales. The interdisciplinary research has developed an internal partnership with the Faculty of Science (Sports Science, Pharmaceutical, *etc.*) and collaboration with over 30 external universities and companies. The materials works have supported many SMEs and large companies (*e.g.* Serco) through Industry 4.0 and EU and international projects in the UK, US, EU and Far East. 15 researchers have used the laboratory each year over the assessment period.

Enhancement in specialist research infrastructure and facilities

The University and Faculty have invested in upgrading the Unit's research facilities with an internal investment of over £3m since 2014. Typically, 70% of the cost of updating research facilities has come from the University/Faculty and 30% from external funding (*e.g.* STFC, ERDF and EU).

Advanced Optical Metrology Laboratory - This is equipped with stabilised dark room facilities, two standard dark rooms, project prototyping and rig building bays, five large optical surface tables, a range of lasers, optical equipment, cameras, sensors and detectors. Other facilities include a Wyko white light interferometer, a Uniscan laser measuring station, a Comet FeinFocus Tiger X-ray Inspection Station, and a high speed, super resolution "pixel shifting" CCD camera system. Five researchers have regularly used the laboratory each year.

Cell Metrology Laboratory - It is equipped with an Asylum Research molecular force probe atomic force microscope (MFP-3D), Zeiss laser scanning confocal microscope (LSM510), Zeiss Axiovert microscope, and a custom, in-house designed and built single optical fibre-based laser trapping system for cell manipulation**.** This cell metrology suite also has a dedicated, fully-equipped cell culture laboratory located immediately adjacent to it. Between 3 and 4 researchers have regularly used the laboratory each year.

Advanced Manufacturing Laboratory - It is equipped with a number of state-of-the-art machine tools (*e.g.* Modified J&S Dominator Grinder, Ultramat Cylindrical Grinder, J&S SAAM Universal Grinder, Bridgeport 5-Axis Machine Centre, Low-temperature Precision Grinder and a mass finishing unit with vibratory feeder). It also has a small, dedicated local metrology facility in an ante-room equipped with Talysurf, Talyrond, laser size measurement, comparator, *etc*. Five researchers have regularly used this laboratory each year.

Laser Surface Micro-Machining and Processing Laboratory - It is equipped with three optical benches, a range of lasers including a 20W 100pS IR Fibre laser, an 8W 532nm DPSS NdYVO4

nS pulsed laser, a 20W nS pulsed 1064nm fibre laser, 350W pulsed YAG laser, and a 400W CW fibre laser. Precision CNC tables and galvanometric scanning heads provide high-speed flexible beam delivery. Around 5 researchers have regularly used this laboratory each year.

Electric Machine and Drive Laboratory - It is equipped with the most-up-to-date research equipment and is oriented towards multiphase machine and drive testing and development. Funding of over £300k from the Faculty and RCIF has provided the laboratory with further pieces of equipment, such as a three-phase to nine-phase matrix converter, four RT-boxes from PLECS with associated software, full PLECS software license, a twelve-phase induction machine, a six-phase permanent magnet synchronous machine with non-sinusoidal flux, FPGA development board, lithium based batteries with a charger, *etc*. 10 researchers have used the experimental facilities in their research in areas of multiphase drives and power electronics.

Micro-Electronic Laboratory - It has acquired wafer level microelectronic probe stations, accessories and semiconductor device analysing equipment with the support of £500k from the University, EPSRC and RCIF. The existence of this facility was instrumental in securing research funding of over £1m from EPSRC during the assessment period (*e.g*. EP/S000259/1, £378k; EP/M006727/1, £350k; EP/L010607/1, £518k). 8 researchers have used the facilities in areas of micro-electronic research.

Consultancies and professional services

During the REF period, consultancy income for the Unit was £1m and grew by 200%. Clients during the REF period included: MoD, QinetiQ, Risktec, Shell, HSE, MCA, Peel Ports, Rolls-Royce, MTC, AECOM, Dublin Ferryport, PERSGA, Greenport (Vietnam), Conway Maritime Trust, Southport and Ormskirk Hospital, Transport for the North, AO.com, ARUP Consulting, MMI Engineering, Merseyrail, Merseytravel, Peloton, Vauxhall, UK DfT, Transport Systems Catapult, and Hi-Tech Steel Services. The income generated was reinvested in research students, and facilities in support of the Unit's research impact strategy for growth.

Supporting impact-generating activities

Close involvement with the Unit's local and international industrial advisory committees has led to a clear emphasis on impact by the members of the Unit. While the members included in this submission have actively expanded their existing impact generation, much effort has been made in developing new industrial impact in both traditional research areas and some emerging research areas (*e.g*. sports materials). For example, a further direct collaboration with BAE Systems (Samlesbury) has demonstrated the efficacy and comparative performance of the new glass media on the finishing of selected Additive Manufacturing (AM) aerospace components (M. Morgan of GERI). The research data was an important reference in the context of their (BAE) recent investment in a dedicated AM production facility and helped shape their high energy finishing and post-processing manufacturing strategy.

The Unit has an agile approach to responding quickly to industrial needs. The Unit has appointed 5 industry-based Visiting Professors to facilitate knowledge transfer and impact generation (*e.g.* Davies from Lloyds Register and Cooper from Risktec). Industrial impact has been generated through their active input to the dissemination of research outcomes (*e.g*. "HSE Guideline for Effective Collision Risk Management for Offshore Installations" with the help of Davies).

The Faculty has a scheme dedicated to giving a commensurate reduction in teaching/administration duties to each academic member for industrial impact-generating activities. The Faculty has also provided funds to support academic member industry visits for possible impact generation and to attend national and international sector conferences. The Unit has covered the annual membership subscription for four professional groups (*e.g*. Mersey Maritime Group representing the regional maritime cluster of more than 1,700 businesses). Furthermore, the Unit has organised impact-generating workshops with invited industry specialists. The Unit has been operating quarterly research seminars since 2014, with a number of industry specialists invited depending on the theme. Industrial speakers make presentations at such monthly seminars on a regular basis (*e.g*. Toye, AECOM) to complement the discussions of on-going research. The Unit, along with the Faculty, has been leading the development of research/industry practice-informed teaching/learning activities such as the

'Design Week' (1 week per semester), where industry speakers deliver guest lectures on current industrial needs and practice.

4. Collaboration and contribution to the research base, economy and society

Support for research collaboration

The Unit has a lively research culture, promoted through monthly seminar programmes held by GERI, LOOM, MEMARC and RCEEE (promoting interdisciplinary opportunities). In all such events, eminent international academics and industrial researchers (*e.g*. Psaraftis, Technical University of Denmark, and Kane, Texas A&M University, USA) are invited to give presentations. Secondments of staff to leading research centres and industry have taken place. These secondments have been funded by both external funding (*e.g*. EU FP7 Marie Curie *REFERENCE, ENHANCE*, H2020 MSCA *RESET, REMESH, GOLF, ENHANCE, PRIGEOC, i-WELD* and *REACTIVE*) and internal funding (*e.g.* the Faculty's pump priming and impact generating schemes). Examples of such secondments include W. Zhang's 6-month secondment at IMEC (funded by the Faculty's Promising Researcher scheme) and X. Ren's secondment of three months at Tsinghua University, China (supported by *PRIGEOC*).

Collaborative research is strongly promoted and supported at all levels in the Unit and Faculty, and is underpinned by the University's Research & Innovation Services, which coordinates initiatives to stimulate internal collaborative working and facilitates external engagement by providing a supportive service in all matters pertaining to intellectual property, patents, commercialisation and legality of contracts. The Unit has also benefited from the match-funding of collaborative activities with industrial partners from the University and Faculty. Examples include 2 PhD projects (*e.g*. with AECOM) match funded by the University, and another 8 PhD projects (*e.g*. with NHS) by the Faculty over the assessment period. The Unit has also received match-funding for 8 PhD researchers on 4 dual PhD programmes with Mahidol University (Thailand), Wuhan University of Technology (China), University of Malaya (Malaysia) and Xian University of Science and Technology (China). Within the University, collaborative projects have been established with colleagues in the Business School and the Faculty of Science on topics including: use of drones in biodiversity; digitalization and display of cultural artefacts; human factor assessment in sports science; sports analytics and digital marketing; quality management; and machine learning in computational galaxy formation and cosmology. Research & Innovation Services and Library & Student Support services jointly organise Research Café events to encourage inter-disciplinary networking and to increase the visibility of research internally, particularly amongst student populations (four times each semester). Each event regularly attracts 30-40 researchers from the Unit.

Interdisciplinary and collaborative research

The research conducted in the Unit is interdisciplinary in nature and as a result requires national and international collaboration and cooperation with researchers in the relevant areas. As part of its strategy, the Unit have therefore developed a strong network of collaborations locally, nationally and globally, working with some of the best-recognised teams in the Unit's key research areas.

Maritime Knowledge Hub - The Maritime Knowledge Hub is gearing up to be a global centre of excellence within the UK (Maritime 2050), providing a national base for marine engineering research, development and decarbonisation as well as high-level technical skills training and business accelerator space.. The University is a strategic partner and Unit researchers have used this platform for external collaboration and impact generation. For example, a project "Liverpool City Region Green Sustainable Travel Corridors" was developed with ERDF funding (*e.g.* "Sustainable Green Travel Corridors", 2019-21, £680k allocated to the Unit, Nguyen) and with ESF funding (*e.g.* "Maritime SuperSkills", 2016-19, £738,800 allocated to the Unit, Jenkinson).

Sensor City and Sensor Platform – The successful delivery of Sensor City since June 2017 and the LCR 4.0 ERDF project based within it has led to the development of a knowledge base where support is given to industrial organisations committed to the development of sensors and IoT. Technical assistance offered includes data automation, embedded electronic systems integration, 3D concept design and digital marketing. One example is the collaboration with the Liverpool School of Tropical Medicine with the support of the Bill and Melinda Gates Foundation

(overall funding over £2m). The sensor technology has been deployed internationally to help reduce the burden of disease such as malaria, and more recently to initiate a sensor platform to detect neglected diseases. The sensor platform demonstrations have also led to successful MoD projects that are moving into a second phase, and continued work with Alder Hey Children's Hospital. Work is also underway with developing sensor platforms for the utilities industry and with numerous SMEs within the region by integrating them for IoT solutions supply chains.

Materials and Manufacturing Research Base with the MTC - This has been formulated following the opening of a new MTC in Liverpool to support manufacturing growth and innovation in the region. The Advanced Manufacturing Technologies (AMT) research area in the Unit has a rich history and has produced world-leading results for its research in manufacturing, measurement and metrology. The most established section of the team is rooted in abrasive technologies, such as grinding, but more recently has excelled at developing vibratory surface finishing using recycled glass. Electronic manufacturing has been represented at LJMU through several UK government- and European-funded development schemes for companies, to help implement new technologies such as surface mount technology, lead-free solder and to meet regulations such as Electromagnetic Compatibility. The research base provides a unique skills mix to help solve any industrial or academic problem. Examples of current project areas include: 1) lifetime reliability assessment and prognostics of manufactured automotive electronics; 2). non-destructive testing and sensing; 3). sustainable superfinishing using vitrified recycled glass; 4). novel application of vibration during grinding, digital manufacturing and Industry 4.0; 5) advanced laser processing and texturing for anti-fouling, cell harvesting, and aerospace composites; and 6) laser polishing of Additively Manufactured components. A range of national and international companies have been attracted to work with AMT, including: ABL, Delphi, Element Six, Finishing Techniques, Holroyd, Ford, JLR, Kistler, Neuteq, QinetiQ, Rolls Royce and Vibraglaz. The well-developed research laboratories have a range of specialist equipment. The capabilities range from general purpose machine shop facilities to advanced digital manufacturing and measurement systems. Many of the AMT systems are novel in-house designs and/or supplemented by unique measurement and signal processing expertise.

Collaborative projects

During the period 2014-2020, the researchers within Unit have coordinated 6 FP7/H2020 projects, and participated in 14 EU-funded projects. 10 multi-partner EPSRC-funded projects were won worth over £4m. The research topics funded through such EPSRC grants include: Electronic Devices & Subsystems; Materials Characterisation; High permittivity dielectrics; Aerodynamics; Mathematical fundamentals of Metamaterials for multiscale Physics and Mechanics; Conservation Ecology; and Environment. 10 InnovateUK projects have been awarded totalling £2m. The research topics include: Information Systems for Railway Stations; the Next Generation of Anilox Rolls; Augmented Reality Maritime Content Platform; healthcare; secure communications in the era of IoT; 5G Testbed; 3D visualization for capturing security requirements and compliance reporting; Additive Manufacturing; and microwave induced plasma technology.

Key research users and beneficiaries

The main beneficiaries, user groups and audiences for the Unit's research include: aerospace engineering and aircraft manufacturers, classification societies, engineering manufacturing industry and service providers, logistics providers, micro-electronic system designers, nano-materials designers, national and international regulatory bodies, offshore renewable system designers and operators, oil and gas companies, port operators, public policy bodies, renewable energy companies, rail operators, maritime stakeholders, UK and EU public and society, and utility companies.

Supporting relationships with industry

The Unit has close relationships with industry, which has enabled identification of the research needs and knowledge transfer to industrial users and active engagement in the transfer of knowledge to industry. Over the assessment period, the Unit has undertaken 10 KTP projects (£1.5m grant awards) with a number of SMEs such as Uplec Industries, Immersive Interactive, Colas, Beverston Engineering, Rapid Prototyping Systems Ltd, AMF Precision Engineering and United Automation. One example is the project with CAL International for the design of a real-

time tracking and mapping system (£242k, 2019-22, led by Johnson). Wider contributions have also been made to benefit different communities and end users from the Unit's research. For example, the LCR 4.0 project (Together-for-Manufacturing, £2.5m ERDF funding allocated to the Unit from 2016 to 2019) has benefited 300 SMEs in the Liverpool City Region such as GeDap, and led to GVA of £31.1m generated and the creation of 50 new jobs (according to an independent summative assessment). The project was acknowledged by the Financial Times as one of the top 100 digital influencers globally. Another example is the Unit's Research Outreach project funded by ERDF (£2.37m, 2013-18) to engage a wide spectrum of industrial partners in low carbon technologies, environment management and renewable energy. More than 50 SMEs were supported in the technology-assisted improvement of their products and services through pilot and feasibility studies and the provision of additional dedicated personnel resources from the Unit.

The Unit has taken every possible opportunity to increase its industrial impact. The members submitted in this Unit have been given training from the Faculty on how to achieve industrial impact through regular seminars (*e.g.* the Transport Knowledge Transfer Network scheme). Such professional training and education programmes have been reviewed on an annual basis, taking suggestions from the industrial advisory committees. For example, acting on a suggestion by an industry member from Peel Ports, the Unit ensures that its 3-D port simulation project takes into account the Liverpool 2 (deep water container terminal) project's design plans.

Contribution to the discipline

The returned members in the Unit have actively contributed to shaping the national and international research landscape during the REF period.

Fellowships - Levi: IEEE Fellow; Election as a Foreign Member of the Academy of Engineering Sciences of Serbia, 2015; **Guo** and **Xang**: EU MSCA Individual Fellowships; **Yang**: ERC Fellowship.

Awards and prizes – Gomm: Best paper award at CompSysTech'14. **Levi**: Outstanding Achievement Award from the European Power Electronics Association, 2014; "Professor Istvan Nagy Award" of the Power Electronics and Motion Control Council, 2018; Appointment as a Distinguished Lecturer by the IEEE Power and Energy Society, 2018; **Nguyen**: Best paper award from ICTIS'19. **Wang**: Award for Risk Reduction in Mechanical Engineering from IMechE in 2018; RINA – Lloyd's Register Maritime Safety Award for Lifetime Achievement; 'Outstanding Contribution to Marine Safety' award for 2017 from IMarEST. **Yang**: Best Paper Award from ALRT'15, QR2MSE'16, IAME'17, 7th IEEE-LISS'17, Emerald Literati Award Highly Commended Paper 2018. **J. Zhang**: "Best Paper Award" of 26th IEEE-IPFA-2019.

Chief Editorships of journals – Levi: IEEE Transactions on Industrial Electronics; IET Electric Power Applications. **Associate/Deputy Editorships – Dordevic:** IET Power Electronics; **Levi**: IEEE Transactions on Energy Conversion. **Wang**: Journal of Marine Science and Technology; Journal of Marine Engineering and Technology. **Yang**: IMA Journal of Management Mathematics; Asian Journal of Shipping and Logistics. **Yu**: International Journal of Automation and Computing.

30 special journal editions including: **Johnson**: International Journal of Distributed Sensor Networks, 2014. **Levi**: IEEE Trans. on Industrial Electronics, 2016. **Nguyen**: Lecture Notes in Computer Science, 2014, 2015, 2016. **Wang**: Journal of Risk and Reliability, 2019.

Keynote & plenary papers – Harvey: VCAS 2020. **Levi**: ElectrIMACS 2014, IEEE-ISIE 2014, 4th EFEA 2016, 12th IEEE-CPE-POWERENG 2018, XI INDEL 2016, ICEMS 2019, IEEE-EUROCON 2019. **Johnson**: 3ICT 2018. **I. Jones**: 10th ESMC2018 **K. Jones**: IT-2017. **Loughney**: WTC'19. **Lu**: 45th IQR'19. **X. Ren**: ACM 2017, GMEE2019, Mechanical Engineering 2020. **Wang**: 24th ESREL'14, 3rd ICTIS'15, MSAS'16, 4th ICTI'17, 2nd MSSS'17, 2nd ICSRS'17, 10th ICIME'18 & IHIP'18, 11th ICIME'19 & 2nd IHIP'19. **Yang**: 6th LISS'16, 5th ICTIS'19, MSSS 2020. **J. Zhang**: IEEE-CSTIC 2015.

Participation in national or international advisory, review, funding, standards or planning bodies - Jenkinson: Advisor on the Ports and Terminals Advisory Group for UK Trade & Investment. **Johnson**: Member of the 'IEEE UK&I Women in Engineering Committee' since 2015, Executive Committee Member of the Rail Research UK Association (2014 to 2018). **Levi**: Served on "GEV9-Industrial and Information Engineering" panel for the national research

assessment exercise (VQR 2011-14) by the Italian National Agency, 2016. **Wang**: Member of the IMO Formal Safety Assessment Experts Group. **Yang**: Advisor of the UK Government for Science on "Future of the Sea" programme.

Organisation of international conferences (general/programme/technical chairmanships) - **Dordevic**: IEEE-IEMDC 2019, IEEE-IECON 2019. **Johnson**: IEEE-PIMRC 2017, HTAS'19, GIoTS 2019. **Levi**: IEEE-IECON 2014, IEEE-IECON 2016, IEEE-IECON 2018. **Nguyen**: 13th EvoSTOC'16, 20th EvoApplications'17, 21st IES'17. **X. Ren**: ACM 2017, Mechanical-Engineering2020. **Wang**: 4th ICTIS'17; 2nd MSSS'18, 5th ICTIS'19, 5th ICSRS 2020. **Yang**: 3rd ICTIS'15. **W. Zhang**: INFOS 2019, ICSICT 2018.