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Global Expert Mission
USA Robotics & AI in Extreme Environments 2019

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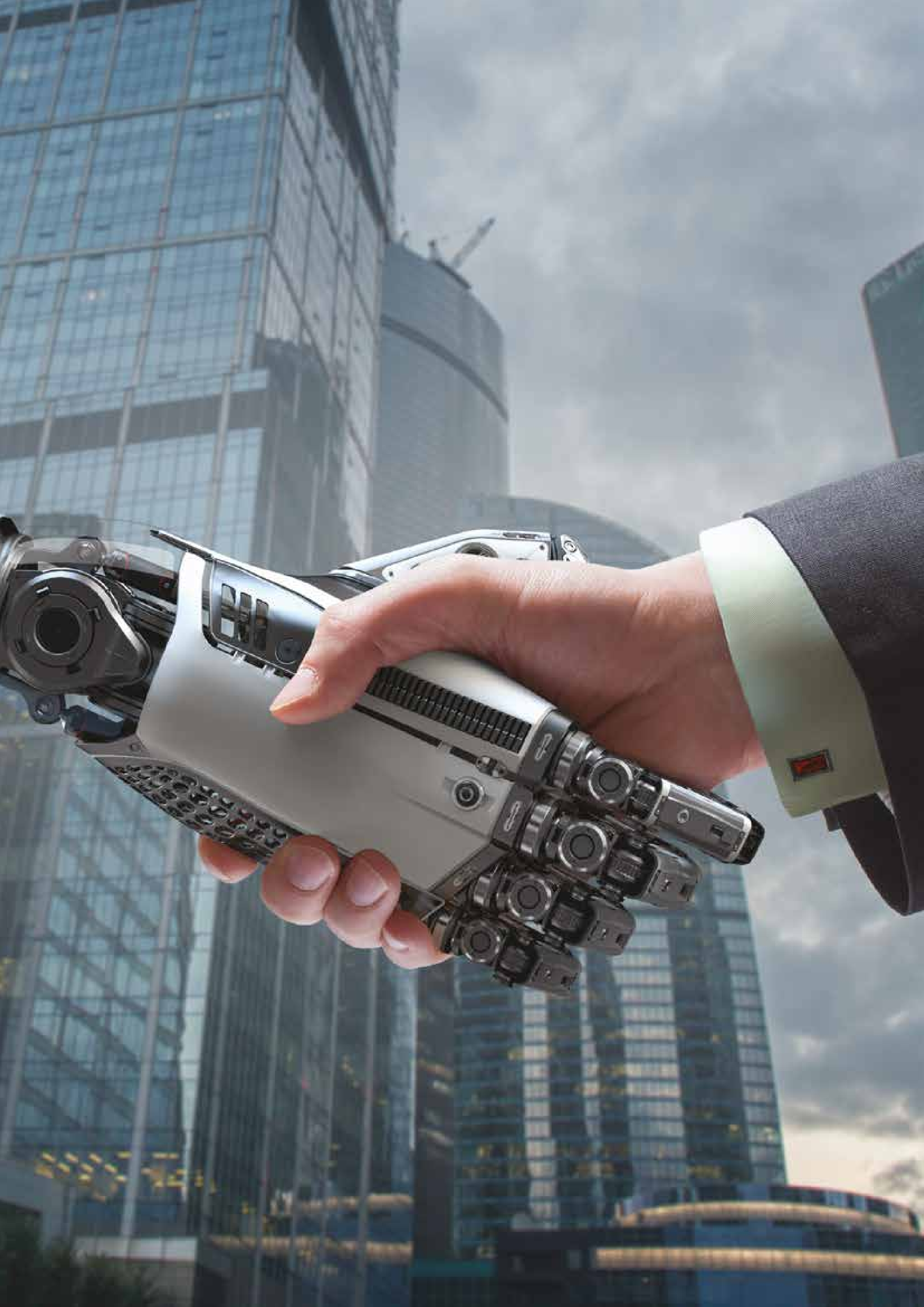

Contents

1. Preface

Innovate UK[1] launched its Global Expert Missions in October 2017 to help UK businesses become truly global enterprises through strategic international innovation collaboration. Delivered by the Knowledge Transfer Network (KTN)[2] in partnership with the UK Science and Innovation Network (SIN), the Expert Missions provide an expert-led evidence base to strengthen Innovate UK's global investment strategy: how and where it should invest to create UK business opportunities in partnerships with key economies.

Each Global Expert Mission will have selected representation from UK business, policy and research community, with the following objectives:

1. Gather market insights and build expert foresights on new and emerging innovation sectors.
2. Identify opportunities for international collaboration.
3. Build a portfolio of technological and business priorities that will elevate the UK as the 'Partner of Choice' in future innovation partnerships with global partners.
4. Facilitate international dialogues for the UK business community
5. Align innovation policy and unlock regulatory barriers for future partnerships.

The USA RAI Expert Mission

The booming robotics and artificial intelligence (RAI) market presents an opportunity for the UK to expand on its expertise in these technologies, build thriving new businesses, solve real problems and lead the debate in critical aspects of what has become known as the Fourth Industrial Revolution (see below).

One of the biggest opportunities for robotics investment and innovation lies in so-called extreme environments, such as space, offshore energy, deep mining and nuclear decommissioning, because environments that are hazardous to human beings are ideal candidates for robotic alternatives – as set out in the Robots for a Safer World Industrial Strategy Challenge Fund (ISCF)[3].

In March 2019 the Robotics & AI in Extreme Environments Expert Mission brought together a cohort of leading experts from the UK's research, start-up, and enterprise communities as specialist representatives of the UK's RAI sector in this field. The team flew to California and Texas to better understand the success of the RAI community in these US states, benchmarking their capabilities against the UK's in extreme-environment applications.

It succeeded in those aims, bringing together an expert group[4] that could form a springboard for new initiatives and cross-industry collaboration in extreme environments robotics. Members came from a variety of disciplines in extreme environments RAI, including offshore energy, mining, engineering, flight assurance, and the development of specialist mechanical devices and AI systems.

Delegates were both informed and inspired by the week-long series of meetings and returned the favour in kind by sharing their insights, research, and experience with their US peers, starting conversations that have continued since the Mission and opening doors to potential new collaboration and long-term commercial opportunities.

At a two-day conference hosted at NASA during the Expert Mission, the Robotics and AI Workshopf[5], delegates heard presentations from a dozen visiting representatives of the UK's four academic Robotics Hubs. Together with Mission members themselves, this gave the UK a delegation of 15 RAI experts in extreme environments at this high-level event: an achievement in itself.

Why California and Texas?

With a GDP of $3t, California is the world's fifth largest economy, which is bigger than the UK ($2.6t). It has become the fulcrum of the US technology sector and is a global centre of excellence in robotics, AI, aerospace, scientific research, Earth sciences, biotechnology, energy, blue-tech (ocean and water technologies) and media & entertainment.

Texas is the biggest US state and the second most populous after California. A GDP of $1.65t makes it the 11th largest economy in the world, and the second largest in the US. Like California, Texas has hothoused world-leading expertise in robotics, AI, engineering, scientific research, energy, and manufacturing.

The Expert Mission seek to establish global growth opportunities for the UK through strategically aligned partnerships with key economies. In a packed and exciting week, the Expert Mission met representatives of numerous RAI businesses, organisations and alliances that are working in sectors characterised by extreme environments, including Space and Offshore Marine, in Los Angeles and San Diego in California, and Houston in Texas. As the two biggest manufacturing states in the US, key industries are being disrupted by RAI technologies.

This report summarises the many insights gathered during the Expert Mission and sets out the numerous opportunities that exist for RAI in extreme environments – technologies that have real cross-sector potential and could help to revitalise traditional industries, create new jobs and boost productivity.

1 www.gov.uk/government/organisations/innovate-uk
[2] www.ktn-uk.org
[3] https://www.ukri.org/innovation/industrial-strategy-challenge-fund/robots-for-a-safer-world/
[4] See Appendix 1 for list of Mission members

2. Robotics and AI: The Opportunities

2.1 A 'Great' Technology for the UK

Robotics and AI (RAI) are critical technologies for the UK's future economic prosperity. 'Robotics and Autonomous Systems' was recognised by the government as one of the 'Eight Great Technologies'[6] in 2013 to support the UK's strengths in science, business, and research.

A range of break-out technologies are associated with Robotics and Autonomous Systems in all types of applications, including extreme environments. A non-exhaustive list includes:

- Unmanned Aerial Vehicles (UAVs) or Systems (UASs) – popularly known as drones – both autonomous and operator controlled.
- Mechatronics, the combining of electrical and mechanical engineering with robotic systems, communications, and computer processing.
- Autonomous vehicles targeted at improving road safety and integrating on-demand transport and delivery networks. Driverless vehicles also have major applications in agriculture, engineering, manufacturing, warehousing, and the supply chain.
- Remotely Operated Underwater Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs), used in deep-sea engineering and maintenance in the oil, gas, offshore electricity, and telecommunications sectors.
- Tele-operation systems, enabling humans to control machinery at a distance.
- Haptic systems, allowing users to grasp objects remotely.
- Sensors and Big Data to detect, measure, compute and process data at scale.
- Microprocessors, including new chip architectures that use less power to carry out AI and machine learning tasks.
- Digital twins – digital representations of physical assets, modelled from live data
- Facial recognition/computer vision systems, both standalone and as components of other system.
- Virtual Reality and Augmented Reality (VR & AR).

Together, these and other innovations, including Blockchain, have become popularly known as the Fourth Industrial Revolution, or 'Industry 4.0' technologies. They are coalescing around super-connected environment the Internet of Things (IoT), with supporting IT infrastructures on premise, in the cloud, or at 'the edge' (low-latency processing close to the point of need). 5G and full-fibre networks are part of this picture too, giving users access to rich media and high-speed mobile communications.

Robotics and automation represent a standalone opportunity for the UK, with numerous sectors, including agriculture, healthcare, transport, manufacturing, and the supply chain, all set to benefit from tasks being augmented or replaced by robots and other connected technologies. Meanwhile, the data that can be gathered by robots will be critical to the design of better, more efficient services – points that will be examined in this report wherever they apply to extreme environments applications.

In 2017, the Centre for Economics and Business Research[7] found that investment in robotics contributed 10 percent of GDP growth in OECD countries from 1993 to 2016, while a separate 1993-2007 study by the London School of Economics[8] revealed that robotics increased productivity in 17 European countries by the same amount as steam technology did during the first Industrial Revolution – but in one quarter of the time[9].

Robots and automation are often misrepresented as 'job killers', but research suggests that these technologies create more jobs than they remove from the economy. In 2018, for example, the World Economic Forum (WEF) published a report, The Future of Jobs 2018[10], predicting a net gain of 58 million jobs to the world economy by 2022 from robotics, automation and AI, with many of them being skilled roles.

2.2 The Extreme Environments Opportunity

According to UK Research & Innovation (UKRI), a greater use of robotics and AI in our society will help to increase productivity, make us more resilient, and create safer, high-quality work for people. In particular, RAI could transform industries that operate in extreme environments, such as nuclear and offshore energy, deep mining and space. Importantly, these systems could also help to improve how

[6] www.gov.uk/government/publications/eight-great-technologies-infographicsrobotics-and-autonomous-systems
[7] https://cebr.com
[8] http://www.lse.ac.uk
[9] https://ifr.org/downloads/papers/IFR_The_Impact_of_Robots_on_Employment_Positioning_Paper_updated_version_2018.pdf
[10] https://www.weforum.org/reports/the-future-of-jobs-report-2018

we deliver industrial and public services. These are the core messages of UKRI's Robotics for a Safer World ISCF.

Extreme environments represent one of the biggest opportunities in robotics, because many of those environments occur in high-value sectors and share the same core challenges: dangerous or lethal locations for humans; poor visibility; navigation problems; tough atmospheric factors; radiation and other hazardous emissions; and communication barriers that make real-time operator control of machines difficult. For these reasons, unmanned technologies spell opportunity for innovators that can develop trustworthy systems.

Put simply, robotics and autonomous technologies are the only means of carrying out some tasks safely and efficiently – or at all – in extreme environments. Combining these technologies with AI capabilities will bring immense added intelligence and cerebral advantages. As a result, the financial payback from sustained central investment in RAI technologies could be transformative for the UK economy, and there is growing demand for innovators to develop systems that can be adapted for extreme uses, have cross-sector applications, and solve real business problems.

The economic prize is potentially enormous, given the types of market that are being disrupted by robotics. For example, according to International Energy Agency statistics[11], global energy investment alone totalled $1.8 trillion in 2017. Recognising the opportunity in this and similar markets, the UK government is supporting the development of technologies that can be deployed in the extreme environments that often typify those industries. According to UKRI figures, this should enable the UK to access a growing global market for robotics and AI estimated to be worth between $1.7t and $4.5t by 2025.

The £200b Nuclear Decommissioning Opportunity

One example of a market that could be transformed by safe, reliable robotics is nuclear decommissioning. In 2018, for example, the Nuclear Decommissioning Authority (NDA)[12] and Innovate UK launched a £8.5m competition to develop robotic technologies to work at Sellafield[13]. At present, decommissioning is slow, dangerous manual work, which costs the UK an estimated £2b a year – an expenditure that is forecast to continue at the same level (not adjusted for inflation) for 100 years. RAI therefore represents a £200b UK savings opportunity to improve and speed up dangerous and inefficient processes.

2.3 UK Investment in RAI To-date

In 2012, the Chancellor of the Exchequer announced £600m of central investment to accelerate the commercialisation of the Eight Great Technologies[14], £200m of which would be targeted at RAI by 2020. The government cited improved manufacturing, medicine and transport as being among an estimated £13b in new UK growth opportunities that it believes could be achieved by 2025 from RAI alone.

As we have seen, high-consequence environments where lives are at risk present a particular opportunity for robotics. Accordingly, the government has invested £93m via the Robots for a Safer World ISCF in projects by industry and academia that are developing new RAI technologies for these scenarios.

Delegates on the RAI Expert Mission all represented organisations that have received ISCF Challenge funding, and UKRI has set aside a further £2m to foster the development of extreme-environment-grade electronics, sensors and photonics for robotics and AI systems. That funding is earmarked for allocation in 2019.

The UK's early move into extreme environment robotics plus the Robots for a Safer World ISCF investment have put the UK in the vanguard of research in this field, sending out a powerful global ambition. A renewed investment in the nation's RAI sector over the next five to 10 years will further maintain the UK's leadership position in extreme environments capabilities and help to strengthen its access to global market potential.

2.4 Industry Sector Deals

There have been other positive investment moves. Under the Industrial Strategy[15], the government has announced a number of new Sector Deals[16] with industry. Relevant deals for RAI include:

- Artificial Intelligence, matching £300m of government investment with £700m from industry and academia. In 2018, the EU unveiled a similar continent-wide strategy, backed by €20b (£17.2b) in central investments – not including national programmes by member states.
- Aerospace, to help this risk-averse sector move to a future that embraces smaller, autonomous, electric, and on-demand systems. However, a number of companies, such as Airbus, are reconsidering their UK plans in light of Brexit – a danger that must be acknowledged.

[11] https://www.iea.org/newsroom/news/2018/july/global-energy-investment-in-2017-.html
[12] https://www.gov.uk/government/organisations/nuclear-decommissioning-authority
[13] https://www.gov.uk/government/news/robots-compete-in-nuclear-decommissioning-challenge
[14] https://www.gov.uk/government/news/600-million-investment-in-the-eight-great-technologies
[15] https://www.gov.uk/government/publications/uk-industrial-strategy-a-leading-destination-to-invest-and-grow
[16] https://www.gov.uk/government/collections/industry-sector-deals

- Automotive, to keep the UK in the vanguard of future mobility trends. But again, several carmakers are moving staff, operations, or investments out of the UK, while others have issued warnings[17].
- Offshore wind, with 'green collar' jobs set to triple by 2030.
- Nuclear, in a deal to secure the industry and drive down costs.

In 2019, the UK government announced its medium-term ambition to raise the national spend on research and development (R&D) to 2.4% of GDP by 2027[18]. According to the most recent ONS figures[19], in 2017 the UK spent 1.69% of GDP on R&D, compared with an estimated EU average of 2.07%. By comparison, Japan invested 3.1%, Germany 2.9%, the US 2.7%, and China 2.1%. South Korea, the country with the world's highest robot density, ploughs nearly 4.3% of GDP into new product development.

Investing in RAI and the other 'Great Technologies' where there is a clear business case – such as extreme environment applications – would be one way for the UK to raise its R&D expenditure to a more globally competitive level, which is revealed to be necessary by the ONS' comparative figures and by the government's own stated aim.

For example, take AI as a standalone market component within RAI. At a Westminster eForum event on AI and robotics policy in 2018[20], PwC forecast that AI will boost global GDP by $15.7 trillion by 2030. China will be the biggest beneficiary of that, it said, adding 26% to the value of its economy. North America will be the next biggest winner with 14.5% GDP growth, followed by gains of 11-12% by major economies in the EU. According to PwC, the UK would lag behind with a 10% GDP increase.

Other countries have recognised the particular opportunity that AI represents within RAI, with 18 announcing national strategies to date including China, the US, Canada, Germany, France, Israel, India, and Japan. Those unveiled in 2018 include:

- Taiwan's AI Action Plan, a four-year programme backed by $1.18b in central funding.
- France's Strategy for AI, a five-year deal that includes $1.75b of government investment.
- South Korea's Artificial Intelligence R&D strategy, which is worth $1.95b.

In such an intense commercial environment in AI, the UK's bold vision through its Industrial Strategy, backed by the Sector Deals and ISCF investments are positive steps to date with smart, targeted investments that have underscored the UK's reputation and competitive differentiator in RAI, particularly in extreme environments. But as global competition intensifies in these critical markets, sustaining and increasing that investment over the next decade will inspire confidence in international partners, bolster the domestic technology market, inspire researchers to commit to the UK as a centre of RAI expertise, and inform the world that the UK is serious about leading the sector.

[17] https://www.bloomberg.com/graphics/brexit-impact-tracker/
[18] https://www.gov.uk/government/speeches/reaching-24-securing-the-research-talent-of-tomorrow
[19] www.ons.gov.uk/economy/governmentpublicsectorandtaxes/researchanddevelopmentexpenditure/bulletins/ukgrossdomesticexpenditureonresearchanddevelopment/2017
[20] https://internetofbusiness.com/ai-16-trillion-wave-will-mainly-benefit-china-says-pwc/

3. RAI in Space Sector

3.1 Introduction: RAI in Space

There are three main reasons for robots and autonomous systems having a key role to play in the space sector. First, until the huge practical, healthcare, safety, and cost challenges of human interplanetary travel are overcome, robots remain the only viable solution for exploring the solar system and beyond at 'first hand' – i.e. in ways that are not possible using astronomy. 'First hand' means a robot hand or sensors gathering data for analysis on Earth.

Robots have further roles to play in extracting resources and deploying infrastructure on interplanetary missions for future human habitation. The US and Europe – including the UK as one of the largest financial and technology contributors to European Space Agency (ESA) programmes – have significant investments in robotic missions to Mars and beyond.

Second, missions to the International Space Station (ISS) and other orbital facilities increasingly rely on robotics and autonomous systems. For example: collaborative robots ('cobots') to help scientists clean and maintain vital installations; unmanned cargo and instrument deliveries from Earth; and robots for assembling equipment in orbit. Interoperability between astronauts and robots, including via wearable robotics, is a vital area of research.

Over the next decade, US plans to return to the Moon aided by private sector partners (see below) will also be supported by robotic elements, such as rovers, landers, mining operations to extract chemicals from the lunar soil, and more. According to NASA's strategic objectives, 'Moon Village' bases will be serviced and maintained by robots in between human missions to the surface.

And third, robotics is a critical element in maintaining terrestrial services that are supplied from orbit. For example, growing numbers of satellite constellations provide location, navigation, environmental, security, surveillance, telecommunications, computing, and data services. As a result, orbital robots – unmanned systems to put satellites in orbit and maintain or upgrade them – are core areas for investment, as are systems to assemble space telescopes, manufacture equipment in space, and catch and remove space debris.

There are other benefits too. Technologies that are developed for space don't exist in a financial, academic, or ethical vacuum in terms of their usefulness on Earth. Resilient, precision-engineered solutions, together with autonomous control systems, robotic hands or grippers, new communications protocols, developments in assurance, and advances in AI and machine learning (ML), are essential for the development of next-generation robots to work in the oil, gas, and offshore wind sectors, for example. Meanwhile, technologies developed for exploring ocean worlds have terrestrial utility, and vice versa.

Agriculture, transport, manufacturing, and healthcare are among the other sectors that will benefit from the advances in precision robotics, mechatronics, autonomous systems, sensors, AI, and computer vision that come from space research – and will also benefit from the vast data sets that these technologies help to gather. These points will be explained in this report.

3.2 The Need for Human-Assisted Technologies

Real-time tele-operation is impossible in some areas of space robotics, because of the latency challenges of communicating with robots that may be long distances from their human controllers. Delays can be extreme: for example, Mars landers and rovers face a minimum comms delay – between Spacecraft Event Time (SCET) and Earth Received Time (ERT) – of around four minutes (or three minutes at light speed), and a maximum delay of about 24 minutes when Mars is 250 million miles away. The average distance between the two planets is 140 million miles, with delays of roughly 14 minutes.

Such time-lags mean that real-time operator control of a robot by joystick is not a viable option. While a robot's objectives are always set by human programmers, it needs to be able to carry them out either automatically or with some degree of autonomy, as the robot responds to the terrain and local conditions en route to mission waypoints. This point was highlighted repeatedly by during the Expert Mission.

This principle of assisted control – described as "supervised autonomy" by speakers at NASA – applies to most robots in extreme environments to some degree. However, outside the many applications where direct human control is impossible or dangerous, the level of decision-making that should be left to machines remains a highly contentious issue. Nevertheless, developing operator-assistance technologies for extreme environments presents a real commercial opportunity, with innovations that can be transferred to other domains, based on human need and ethical considerations.

[27] www.wired.co.uk/article/google-deepmind-nhs-health-data
[28] www.bcm.edu/departments/surgery/research/innovate

In May 2019, experts at the European Space Agency (ESA) centre in Oxfordshire completed a series of tests[21] in the Atacama Desert, 6,900 miles away, to see how the Rosalind Franklin Mars rover reacts to even a small communications delay. The rover will be launched in August 2020 as part of ESA's ExoMars Mission and is due to land in March 2021. With £250m invested in the programme, the UK is the second biggest contributor after Italy, according to government figures.

3.3 New UK Commitments to Space Sector

In June 2019, the UK government signalled its strong commitment to the space market with the launch of two new initiatives – a National Space Council and National Space Framework[22] to provide strategic leadership across government and to coordinate all aspects of the UK's space strategy and investment.

It stands to reason that RAI will have a key role to play in this strategy, given the extent to which so many aspects of the market are now being driven by robotics (as outlined above), and given that innovators are developing new robotic systems to assist in other aspects of space. These issues will be explored throughout this part of the report, especially in the sections describing Expert Mission meetings with NASA.

Further in June 2019, the government announced[23] funding of up to £20m for Spaceport Cornwall and for US operator Virgin Orbit to develop facilities for small satellite launches from Cornwall in the early 2020s[24]. This will enable the UK to compete for a share of a global market for launching small satellites that could be worth £3.9b by 2030. As set out above, RAI can play a critical role in maintaining satellite constellations.

Meanwhile, the UK Space Agency and ESA are to collaborate with NASA and the US National Oceanic and Atmospheric Administration (NOAA)[25] on science, space, and ground systems technology. NOAA and ESA, with support from the UK, are to launch two weather monitoring spacecraft in the next five years.

According to ONS figures, UK exports by space sector are set to grow to £25b by the end of the next decade. This would meet the industry and government target for exports to contribute 60% of the UK's space sector revenue by 2030, up from 37% in 2017. In 2016-17, UK space exports were worth £5.5b. In the same year, the UK space industry supported 41,900 jobs, with nearly one-fifth based in Scotland. Robotics could be a key component of the UK's growing commitment and influence in this area, in line with current trends in the sector.

3.4 Expert Mission Engagements with Space Sector

3.4.1 NASA Lyndon B. Johnson Space Center (JSC)

The Expert Mission visited the Robotics & Simulation Division at the NASA JSC[26] in Houston, Texas, the independent agency whose focus is humans and the systems they use in space. The JSC is also the home of large-scale engineering, humanoid robot development (see boxout), and Mission Control for human space exploration, among other facilities. The delegation was hosted by Robert Ambrose, Chief of the Software, Robotics & Simulation Division.

3.4.1.1 Return to the Moon 2024

During Expert Mission week in March 2019, the US government set NASA a strategic objective of returning to the Moon by 2024[27]. The following month, China announced plans to establish a base at the lunar south pole within a decade: a new Space Race is on. The JSC explained that the immediacy of the US challenge opens up partnership opportunities for NASA to exploit existing or third-party technologies, rather than develop everything in house. The space agency will build digital simulations of every facet of the missions, then combine and compare these models with live data to train crews on equipment.

Autonomous systems will be critical to the missions and to future expeditions to Mars; equipment will be pre-deployed and left unattended for long periods between human visits, so will need to continue functioning independently. For humans, individual missions are likely to be two-week (one lunar day) and six-week (two lunar days, one lunar night), making use of a permanent robot- and AI-maintained facility, the Gateway. Creating equipment that can survive the "cryogenic" lunar night and the searing heat of lunar afternoon will pose new challenges – a further partnership opportunity for the UK.

While the final budget for these missions has yet to be published, NASA reports[28] that the initial request included a budget of $21b, to which $1.6b has been added for 2020. This puts the current budget at $4.5b a year over five years, with further annual supplements likely.

[21] https://www.gov.uk/government/news/mars-rover-gets-work-out-controlled-from-more-than-6000-miles-away
[22] https://www.gov.uk/government/news/leading-the-new-space-age-government-backs-ambitious-plans-for-the-uk-in-space
[23] https://www.gov.uk/government/news/leading-the-new-space-age-government-backs-ambitious-plans-for-the-uk-in-space
[24] https://spacenews.com/u-k-to-fund-development-of-spaceport-facilities-for-virgin-orbit/
[25] https://www.noaa.gov
[26] www.nasa.gov/centers/johnson/home
[27] https://www.nasa.gov/feature/sending-american-astronauts-to-moon-in-2024-nasa-accepts-challenge
[28] https://www.nasa.gov/sites/default/files/atoms/files/nasa_fy_2020_budget_amendment_summary.pdf

Partnership Opportunities

- Asked by delegates whether the private sector would be involved in these missions, NASA confirmed that this will be the case, thanks to the advent of the commercial space market (such as robotic cargo deliveries to the ISS). These new approaches will inform the 21st Century strategy, with opportunities for ESA and its affiliates – and therefore the UK. Accordingly, the UK should consider creating a Lunar Challenge Fund to develop RAI solutions for the Moon, which, like many extreme environments systems, could have numerous other commercial applications.
- At the end of May 2019, NASA announced its first lunar mission deals with three robotics start-up companies: Astrobotic, Orbit Beyond, and Intuitive Machines[29].
- There may be opportunities to sell tools to NASA for the missions, and to assist with software testing and autonomous control systems development. However, Expert Mission delegates expressed concern over the difficulty of obtaining US government contracts, particularly in the case of UK start-ups. A more direct and promising route to NASA collaboration is likely to be through one of its long-established US engineering partners, such as Jacobs (see separate entry, below).
- Another requirement will be for the development of small, autonomous logistics landers for delivering supplies to the surface, while a further opportunity might be in developing facilities that can extract chemicals from the lunar soil to help bases become self-sustaining. NASA's vision is of autonomous robot teams collaborating and interoperating with humans at the Moon Village/Gateway facilities.
- Other space agencies may be able to contribute small rovers, which could be charged or carried by larger vehicles. It was emphasised that any partner country or organisation would be free to deploy its own technologies and science experiments on lunar missions, as long as they delivered NASA's contractual requirements.
- The JSC online Partnerships Gateway[30] lists specific challenges where NASA is seeking co-development relationships, including with private companies. Steven A Gonzalez is Chief Technology Transfer Strategist for the JSC and would be the main point of contact.

Any direct relationship with the space agency would involve signing a Space Act Agreement – the legal convention that empowers third parties to support NASA's strategic mandate. This would be the bottom line in any partnership.

[29] https://arstechnica.com/science/2019/05/nasa-picks-three-companies-to-attempt-moon-landings-in-2020-and-2021/
[30] https://www.nasa.gov/centers/johnson/partnerships/JSC-Partnership-Gateway

NASA's Humanoid Robots

Valkyrie

One recent example of a Space Act Agreement (SSA) is the deal with Edinburgh University (http://valkyrie.inf.ed.ac.uk), which has one of NASA's $2.5m Valkyrie robots on site (built for and owned by the university, and serviced by NASA). A future version of the Valkyrie humanoid may walk on Mars or work in disaster recovery. The modular, female-persona development platform was developed with assistance from engineering company Jacobs.

The Edinburgh research project in robot balancing, manipulation, and human-co-working supports NASA's strategic aims, with funding for the research provided by the UK Space Agency. "When that robot walked into the lab, that university went to the front of the field of robotics," said Ambrose. Edinburgh then became part of the JSC's open source collective, pooling research findings and software with NASA and with other universities worldwide.

NASA Valkyrie robot

Robonaut

The NASA JSC has also developed the Robonaut 2 humanoid, which is designed as a 'cobot' to work as part of an integrated team on the ISS. Jacobs procured parts, designed hardware, and assisted in assembly and certification.

Researchers are training these robots to understand natural language commands, and to recognise and grasp objects, such as screwdrivers – a task they will have to carry out safely in the hazardous environment of a space capsule. The development challenges of training robots to see objects (using point clouds, for example) are complex and time-consuming, but represent a significant commercial opportunity. The space agency is working with popular tools such as Google's Tensor Flow and Voice API to break the task down into smaller, meaningful chunks.

In April 2019, NASA unveiled its new Astrobee robots: free-flying, cube-shaped cobots that are designed to assist astronauts on the ISS, monitor experiments, and act as microgravity research platforms. In the long term, these and other collaborative robots' ability to be trained to carry out new tasks could create commercial applications in other hazardous environments – e.g. in the oil and gas sectors.

Useful NASA Links

- Procurement office: www.hq.nasa.gov/office/procurement
- SBIR/STTR programmes: http://sbir.nasa.gov
- Small Business Procurement: http://osbp.nasa.gov/business.html
- Unsolicited company proposals: http://prod.nais.nasa.gov/pub/pub_library/unSol-Prop.html
- Unsolicited grant proposals: http://go.nasa.gov/2HSgvll
- Research opportunities: http://nspires.nasaprs.com/external/

3.4.2 NASA Jet Propulsion Laboratory at the California Institute of Technology (Caltech)

NASA's Jet Propulsion Laboratory[31] at La Cañada Flintridge, Pasadena, California, is a federally funded research and development centre (FFRDC), managed and staffed by Caltech for the agency. Its 1930s roots in rocket research predate the foundation of NASA by over 20 years. Today, it is its principal spacecraft technology research centre. Alongside deep-space exploration, much of the JPL's work now centres on the development of robotic systems – including landers, rovers, and UAVs – to explore the surface of planets, asteroids, and comets, and new communication and control systems for them.

3.4.2.1 Mars Robotics

The JPL has a particular focus on developing robotic and autonomous systems to explore Earth's nearest planetary neighbour, Mars. Internal JPL research programmes funded by NASA include the development of swarms of autonomous rotary-wing UAVs (rotorcraft), and the Mars Science Helicopter. The latter underwent its first test flight in a vacuum chamber at the JPL on 28 March 2019. These lightweight robots will need to be capable of flying in a Martian atmosphere that has one percent of the density of Earth's and consists mainly of carbon dioxide, but they will be aided by Mars' lower gravity. Using rotorcraft, scientists will be able to examine large areas of the surface quickly.

Other NASA-funded Mars programmes include autonomous sampling of gas and close-up flyby imaging; unfolding robots; machine-learning-based analytics for rovers; underwater mobile manipulation systems and the Ice Worm robot, which is capable of climbing icy slopes. These technologies have many commercial applications. For example, swarming, surveillance, sensing, sampling, and autonomous operations systems could all be adapted for search and rescue, emergency response, disaster zone monitoring, infrastructure maintenance, and more. The extent of the commercial opportunity is why the UK needs an ongoing investment strategy to match its expertise in these areas.

Partnership Opportunities

The JPL meeting was hosted by Dr Adrian Stoica, Programme Manager in the Office of Strategic Planning, who indicated that companies can approach the JPL to license NASA technologies. For its part, the JPL buys tools and products, rather than IP. The close partnership between NASA and ESA – for example, NASA has technology onboard ESA's ExoMars rover mission – means that existing collaboration channels with NASA are open for the UK at ESA level for RAI opportunities

According to Richard T French, Manager of Technology Partnerships at the JPL's Office of Space Technology, JPL is now more interested in establishing external relationships and bringing in technology from outside. Mr French would be the main point of contact in what he described as a \$60-\$70m programme for small businesses and innovators are encouraged to focus on NASA's needs and on reducing friction for the organisation. This focus on business needs applies to working with clients across the extreme environments RAI sector: a key learning from the Mission.

There certainly are signs that the JPL is starting to engage more with start-ups, as private companies and investors become involved with space exploration. This was evidenced by the Mission's joint meeting with Techstars, Starburst, and the Aerospace Corporation.

[31] www.jpl.nasa.gov

Virtual Exploration

At the JPL, the Mission witnessed an innovative use of Microsoft's HoloLens AR headsets, which could be emulated in a variety of industries. Demonstrated by Victor Luo, General Manager at the JPL's Operations Lab, NASA's OnSight application gives scientists anywhere in the world a virtual presence and meeting point on Mars (see https://mars.nasa.gov/resources/22086/screen-view-from-onsight/)

Using detailed images gathered by robots and satellites, the HoloLens headsets are used for an immersive, 360-degree view of the Martian terrain. Wearing headsets, Earth-based scientists can walk around this as avatars and bring up detailed sensor data from the surface of Mars from each pixel in the 3D reproduction. Similar applications allow NASA engineers to explore full-resolution CAD models of space stations and other installations – a use case that could be emulated in the manufacturing, engineering, and energy sectors, using digital twins.

VR images of Martian surface and Curiosity rover in the JPL Operations Lab

3.4.3 Techstars Starburst Space Accelerator
In March 2019, the JPL announced the launch of the Techstars Starburst Space Accelerator[32], a new Los Angeles-based start-up development programme co-funded by Techstars and based within the Starburst Aerospace Accelerator (see below). It focuses on "the next generation of space technology companies and related frontier technologies".

Alongside Starburst, Techstars, and the JPL, founding members include the US Air Force, Lockheed Martin[33], Maxar Technologies[34], SAIC[35] and Israel Aerospace Industries North America[36]. The partners aim to create "the most vital accelerator for building ecosystems and solving big problems in the space sector". The strategy is to identify ten start-ups to join each of the scheme's three-month bootcamps, and then "blow wind in their sails".

Although the programme is US-based and -focused, there are precedents for UK start-ups competing successfully at such accelerators. For example, the TMCx[37] programme at the Texas Medical Center in Houston has boosted a number of British innovators in the field of Digital Health (see the 2019 US Digital Health Expert Mission report). However, the overall aim of such projects is invariably boosting employment at state level and encouraging start-ups to incorporate in the US. They present a significant opportunity for UK innovators, but the challenge is retaining the benefits within the UK economy. The 2019 deadline has passed for applications to the

32 www.techstars.com/programs/starburst-space-program/
33 https://www.lockheedmartin.com/en-us/index.html
34 https://www.maxar.com
35 http://www.saic.com
36 https://iainorthamerica.com
37 https://www.tmc.edu/innovation/innovation-programs/tmcx/

inaugural cohort in July, with the first Demo Day scheduled for October, so the UK should pursue opportunities to participate in 2020 and beyond.

3.4.4 Starburst Aerospace Accelerator

The Expert Mission was hosted by Vandad 'Van' Espahbodi, Co-founder and Managing Partner of the Starburst Aerospace Accelerator[38] in Los Angeles. Starburst has been launched to access start-up and SME expertise in those sectors, around which innovations in electric flight, rocket systems, small satellite technology, and autonomous operation now revolve. For Starburst, aerospace is a broad term: the organisation works with OEMs, Tier-1 and Tier-2 suppliers, operators in space and on the ground, and with maintenance, repair, and operations (MRO) providers that support the value chain.

As with the new Space Accelerator programme, the parent organisation's strategy is to help innovators gain commercial traction within a powerful sector, including technology scouting and advisory work to help the "old guard" of aerospace work with newer, smaller companies and adopt their technologies.

The UK's entrepreneurship and skills initiatives, particularly Innovate UK and the Catapult programmes were praised and suggesting that the US can learn about efficient technology adoption from. The UK is viewed as setting "powerful precedents" for how a new AI-, robotics- and automation-assisted workforce will work with data. By contrast, the US focus is largely on creating jobs, he said. However, the UK could do more to amplify its achievements as competitive differentiators.

The meeting at the Starburst Aerospace Accelerator stressed the importance for RAI innovators to learn how extreme environments technologies could be applied in different domains – not just aerospace, but also energy, mining, and agriculture. UK innovators should find ways to transfer their capabilities into a US presence – a common message from US accelerators. Meanwhile, established businesses should not try to do everything themselves, but should instead look at ways to transfer their knowledge into new entities.

Starburst is seeing novel use cases where partners create channels to market for others in exchange for first refusal on technologies. Meanwhile, US universities are creating task forces to commercialise their innovations. Being innovative isn't enough – the secret of success is demonstrating how innovators have inserted their technology into real-world commercial programmes – or that they have the potential to do so.

3.4.5 Techstars

Techstars[39] in Boulder, Colorado, is a commercial seed accelerator, founded in 2006 in Colorado. Managing Director Matt Kozlov described the company as one of the most active Series-A investors in the world, ploughing money into about 1,800 companies globally – 90 percent of which are still active or have been acquired.

Techstars operates globally through a network of 47 accelerators. Half of these are industry agnostic – for example, Techstars London – and half are vertically focused. In the latter case, the accelerator picks 10 companies and brings them together under one roof for an intensive, 90-day mentoring programme. Techstars defines the space sector broadly to include companies that are innovating in adjacent markets, such as energy, mining, and autonomous systems for harsh environments. This is because there are "more direct commercial paths to success than targeting the US aerospace and defence sectors".

De-risking the use of autonomous vehicles through sensors and LiDAR were identified as particular area of focus.
But in every case, the organisation wants to help start-ups build viable, commercial businesses – improving their pitches, starting conversations, and securing funding – while lowering barriers to entry in government. That said, it was acknowledged that there are fewer opportunities available to non-US companies, hence the encouragement to incorporate in the US.

3.4.6 Aerospace Corporation

The Aerospace Corporation[40] in El Segundo, CA, is a federally funded, non-profit R&D centre, focused on aviation and space technologies. These range from components, assembly, integration, and testing, to launch, deployment, data links, processing, and the planned end-of-life of systems. The company also has interests in drone tracking for security purposes – a crossover with Mission members working in autonomous flight and systems assurance.

Commercial Opportunities

Director of Innovation Development, Andre Doumitt, runs the Innovation Lab (iLab)[41], which handles internal R&D for the corporation, as well as managing external relations

[38] http://starburst.aero
[39] www.techstars.com
[40] www.aerospace.org
[41] https://aerospace.org/paper/fostering-innovation-aerospace-1

with universities, start-ups, accelerators and incubators. The purpose is to identify innovations that will help make clients' strategic space ambitions a reality, and the organisation is actively seeking partners for the aerospace sector. The iLab acts as a bridge across a fragmented provider space, a challenge he explained is mirrored on the demand side. The unit seeks to break down obstacles to getting new technologies to end users – something that other US technology/investment alliances are also focused on doing.

In robotics for extreme environments, a number of horizontal and vertical sectors touch on aerospace. Various commercial opportunities in analysing space data, managing an overload of rich media information, and in commercialising the imagery collected from satellite constellations. The latter could offer new intelligence-based services to innovators in real estate, finance, agriculture, and other sectors, suggesting that start-ups need to think outside the box to commercialise their work. With 75 private companies now working in the small satellite space alone, this represents a growing opportunity.

The core message was that RAI specialists need to consider the (fragmented) buyer market and focus on reducing friction for their customers, solving real problems, and demonstrating a deep understanding of their businesses. In delegates' views, this was one of the core messages to emerge from the Expert Mission.

3.4. 7Northrop Grumman

The Mission was invited to the campus of aerospace and defence giant Northrop Grumman[42] in San Diego, CA, which last year reported net income of $3.2b on global sales of $30.1b, 85 % of which came from the US market.

The meeting comprised a limited tour of campus facilities and a presentation of the company's autonomous defence systems, which are now core to its activities. The portfolio includes the Global Hawk[43] surveillance platform; Fire Scout[44] autonomous support helicopters, the Bat[45] family of medium-altitude reconnaissance aircraft and the semi-autonomous X-47B[46] plane, which is optimised for naval operations and capable of both autonomous mid-air refuelling and landing on aircraft carriers.
As a largely US-focused defence company, the meeting perhaps offered little realistic opportunity for partnership in the US defence sector, compared with companies that have a UK presence, but visits to the research labs for the Fire Scout and X-47B platforms underlined some key aspects of the company's approach to RAI:

- Unmanned craft and autonomous systems (the company manufactures both) minimise the cost and risk of air missions – military or otherwise – extending their range and usefulness by reducing weight and increasing fuel and payload capacity. In other words, many unmanned aircraft can fly further for longer, and (for example) deliver more cargo to more people, reducing the risk for human beings in dangerous situations.
- Human supervisors are in the loop of critical decisions, with autonomous systems following pre-set missions while adapting flight behaviours independently to weather conditions and other factors. This was Northrop Grumman's own definition of autonomy within its product line.
- Remote-control facilities may allow each operator to supervise more than one craft, lowering staffing costs.
- The development of platforms such as the X-47B is heavily focused on the enabling software.
- All unmanned systems are simulated and tested digitally first, and physically modelled in labs before prototypes are built. The extent of the company's simulated environments was impressive.

[42] www.northropgrumman.com
[43] https://www.northropgrumman.com/Capabilities/GlobalHawk/Pages/default.aspx
[44] https://www.northropgrumman.com/Capabilities/FireScout/Pages/default.aspx
[45] http://www.northropgrumman.com/Capabilities/BATUAS/Pages/default.aspx
[46] http://www.northropgrumman.com/Capabilities/X47BUCAS/Pages/default.aspx

4. RAI in Offshore Marine Sector

4.1 Introduction: RAI at Sea

The Expert Mission met companies, non-profits, and other organisations in the field of marine robotics. This forms one part of the much larger sector known as blue-tech, which covers both ocean technologies and innovations in the water sector. Delegates also met providers in related disciplines such as AI-enabled navigation and the maintenance of energy installations by land, sea, and air.

Combined with data analytics and AI systems, surface robots are also providing environmental services, such as mapping the spread of plastics pollution in our oceans and monitoring marine life. They are also increasingly seen as delivery platforms for both subsurface and airborne robots. Marine robotics includes Unmanned Surface Vehicles (USVs), such as Wave Glider from Liquid Robotics[47]. Seaborne drones are increasingly being used in applications such as offshore infrastructure inspection, often teamed with UAVs.

Underwater robotics embraces subsea autonomous or semi-autonomous systems, such as Remotely Operated Underwater Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs), the former usually tethered to subsea stations or surface vessels, the latter not. Launched directly or from ships, robots like these have widespread construction, maintenance, and engineering applications in the energy and telecoms sectors. In these scenarios, robots and humans need to access, operate, or repair installations such as undersea pipelines, cables, and valves in hazardous conditions, using grippers and other tools.

4.2 Marine Challenges and Opportunities

Under the sea, the combination of cold, pressure, lack of oxygen, darkness, buoyancy, and sometimes extreme weather, has strong parallels with space exploration. Indeed, astronauts train underwater for space missions and many spacecraft systems are tested in water tanks. There are further parallels with deep mining and autonomous transport, where navigation through complex, unstructured environments is a shared development challenge for AI, ML, and computer vision systems.

One challenge that underwater robotics shares with space applications is delayed or low-data-rate communications: radio waves propagate badly in salt water, because it is an electrical conductor. This means that high-speed/high-definition comms between humans and robots are a challenge on/under seven-tenths of the Earth's surface – the sea – almost as much as they are in space.

Beneath the waves, GPS may also not be an option. High-speed acoustic modems or low-frequency communications systems are more reliable than alternatives underwater but offer lower data rates than terrestrial high-speed connections. Put another way, undersea communications are at the early-90s dial-up modem stage, unless robots are tethered to ships or buoys that have satellite links.

As a result, human-assistance and semi-autonomous operations will be just as essential to the disruption of maritime sectors as they are in other extreme environments, such as space. At the same time, undersea communications infrastructures for robots will be a major growth area.

The takeaway once again is that RAI technologies developed for one location can be adapted for use in others. This represents a significant commercial opportunity, with providers typically having expertise across multiple domains.

A Sea of Opportunity

Other aspects of the marine environment are ripe for disruption. As with functions such as maintenance, transport, logistics, and the supply chain on land, most marine processes are slow, inefficient, resource intensive, and extremely expensive. This is why some innovators, such as Houston Mechatronics (see below) are exploring the creation of a new on-demand service-based economy for robotics. In this application, the business model is not about selling expensive robots – a difficult market to profit in at scale – it's about selling the services and convenience that they provide. Several organisations made this point to Mission delegates.

In these instances, AI and ML become the critical elements, as the service becomes focused on the intelligence and adaptability that robots can offer the customer. In some instances, the AI and data can be decoupled and sold as a service to specialist hardware companies – see Mission meetings, below, for some examples of this.

However, traditional service providers will try to protect the income streams that come from expensive, locked-in processes, a challenge that can be seen as analogous to market tensions over Uber and other disruptive digital service providers on land.

[47] https://www.liquid-robotics.com

4.3 The UK's Current Stake in Offshore Marine RAI

The UK has several marine technology centres, such as those in Portsmouth, Southampton, Plymouth, Liverpool, the South West Marine Cluster, and more. More directly related to the Offshore Marine sector, the UK has already established organizations and programmes for Offshore Energy and the use of RAI technologies such as:

- The Oil & Gas Technology Centre (OGTC)[48] was established in October 2016 with £180m funding as part of the Aberdeen City Region Deal. An industry-led research and knowledge organisation, it is backed by both the UK and Scottish governments to fund and direct projects that help to unlock the full potential of the UK North Sea. Its objective is to be the go-to technology centre for the oil and gas industry in the UK and internationally by transforming ideas into solutions
- The Offshore Robotics for Certification of Assets (ORCA) Hub[49], a £36m programme aiming at addressing the offshore energy industry's vision for a completely autonomous offshore energy field. Launched in October 2017, it is part of the government's £93m R&D funding on "Robotics and AI for Extreme Environments" through the Industry Strategic Challenge Fund (ISCF).

In May 2019, soon after this Expert Mission, the UK Government announced its backing for a multimillion-pound Global Underwater Engineering Hub in Aberdeen[50], bringing together underwater technologies from industry and academia to build on UK expertise in subsea robotics, ROVs, and maritime support vessels. "Seizing the opportunities in the blue economy will also help the UK's oil and gas sector diversify and support the UK move away from fossil fuels towards clean growth," said the announcement.

According to government figures, the UK has a 40% share of the global market in underwater engineering and is in prime position to capitalise on an industry that could be worth more than £100b globally by 2035. The UK's oil and gas sector supports around 280,000 jobs, meets almost half of the country's energy needs, and has contributed £334b to the economy.

4.4 Expert Mission Engagements with Marine & Underwater Sector

4.4.1 The Maritime Alliance

San Diego, CA, is the largest ocean and water technology centre in the US, and has a significant Navy presence. The Expert Mission met a broad spectrum of local blue-tech specialists at a session hosted by the Maritime Alliance (TMA)[51]. With over 100 members, TMA is a non-profit industry association and cluster organiser for the maritime tech community. It focuses on building sustainable, science-based ocean and water industries and jobs, and is forging strong links with policymakers in California.

The organisation also has an educational and outreach remit and is co-founder of the BlueTech Cluster Alliance (BTCA)[52] of ten leading blue-tech clusters in eight countries. This includes two in the UK: Marine South East and the Cornwall Marine Network. Clearly, channels are open between the US and UK for blue-tech innovation and for a close working relationship.

Michael B Jones, President, and Shara Narsipur, Project Co-ordinator, represented TMA at the roundtable. With local clusters in the UK, US, Canada, Ireland, France, Spain, Portugal and Norway already members of the BTCA, this suggests that real momentum is building in the sector.

Robotics and AI are core to this increasingly global movement. At the meeting were representatives from long-duration sailing drone specialist SubSeaSail[53], surface and subsea UAV developers Ocean Aero[54], autonomous platform experts the Unmanned Systems Operations Group[55], ship-launched drone company Planck Aerosystems[56], ocean- and Earth-science research centre the Scripps Institute of Oceanography[57], subsea tech provider Teledyne Marine[58], geophysical services company ION[59], engineering consultancy Quartus Engineering[60], surveillance systems supplier Sidus Solutions[61] and the US Navy[62].

[48] https://www.theogtc.com/
[49] https://orcahub.org/
[50] https://www.gov.uk/government/news/scottish-underwater-engineering-base-to-propel-uk-to-the-top-of-blue-economy
[51] www.themaritimealliance.org
[52] https://www.bluetechclusters.org
[53] https://subseasail.com/
[54] https://www.oceanaero.com/
[55] https://www.linkedin.com/company/unmanned-systems-operations-group/?trk=companies_directory
[56] https://www.planckaero.com/
[57] https://scripps.ucsd.edu/
[58] http://www.teledynemarine.com/
[59] https://www.iongeo.com/
[60] https://www.quartus.com/
[61] https://www.sidus-solutions.com/
[62] https://www.navy.mil

The US Navy's Space and Naval Warfare Systems Command (SPAWAR)[63], represented by its Deputy CTO, Wadad Dubbelday, is researching autonomy and teaming in unmanned platforms in collaboration with industry and academic partners. There was an expressed an interest in the LiDAR and remote-inspections research being carried out by some Expert Mission delegates, particularly on human-machine interfaces.

Also, the US Department of Defense[64] now recognises the need to be more agile in finding new technologies, such as by working with external partners. Whether that might include UK innovators is an open question, but the blue-tech clusters provide a potential communication channel.

According to Gwen Nero, Director of Corporate Affiliates at Scripps Institute of Oceanography, the organisation has expanded its strategic research in recent years. Innovative technology is a priority area, with a focus on AI, data management, and analytics, so there is clear potential for ongoing dialogue with Scripps.

Commercial Opportunities

- TMA is not aware of the existence of any specialist ocean technology investment or seed funds in the US or UK, so there is strong potential for establishing these in the future. The Alliance and UK clusters could be powerful allies in convincing institutions of the benefits of creating such funds. Arguably, this is an open goal for the UK.
- Blue-tech is "one of the great opportunities in the world" driven in part by robotics and autonomous systems. These are enabling human beings to explore the planet fully for the first time – and persuading them of the need to preserve it. This throws down the gauntlet to the technology community to do better at spreading positive messages. The UK Missions delegates were advised to be upfront about looking for business partners or funding when introducing themselves at US meetings.

New UK-US Marine Partnerships

The Maritime Alliance (TMA) had a big presence at the Ocean Business (www.oceanbusiness.com) trade show in Southampton in April 2019, one of the UK's biggest ports and home to the National Oceanography Centre (NOC). Southampton is also a marine and aerial robotics hotspot, via the drone research teams at Southampton University.

At the event, the US and UK governments hosted a 'best practice exchange' for blue-tech SMEs, at which companies learned how they could benefit from the Mutual Recognition Agreement (MRA) on marine equipment, signed by both governments in February 2019. Under this deal, designated products that comply with US standards will be accepted for sale in the UK without additional testing, and vice versa.

[63] https://www.public.navy.mil/SPAWAR
[64] https://www.defense.gov

4.4.2 Oceaneering

Oceaneering[65] at Houston, TX, is a global subsea engineering and applied technology provider, with 9,500 employees and roughly $2b in revenues. With 60 locations in 23 countries, it focuses on marine engineering and maintenance – particularly offshore oil and energy via ROVs, subsea hardware, remote asset-testing, inspections, project management, and surveying & mapping services. It also has a track record in developing robotics, automation, tele-operation, and telemetry management systems for aerospace and defence.

Oceaneering has notable side-lines in motion entertainment systems, including trackless rides for theme parks, and in automated guided vehicles (AGVs), which carry loads in warehouses and factories. This underlines the point that autonomous and mechatronic systems developed for one environment have commercial potential in others.

The Expert Mission met Peter Moles, Director of Emerging Technologies, Carl Walz, former NASA astronaut and now Director of Business Development for Space Systems, and Jud Hedgecock, Director of Robotics for Space Systems. In Oceaneering Aberdeen, Steven Cowie would be the contact for UK partnerships.

Disrupt or be Disrupted

The marine engineering and services sector is ripe for disruption, but Oceaneering's global presence and traditional customer and investor base make that a challenge for its RAI competitors. Meanwhile, it would see itself as being part of the disruption.

The company has what it describes as "the world's largest work-class ROV fleet" – 337 undersea robots, depth rated to 4,000 metres. According to Oceaneering, this represents 36%of all the world's ROV assets in this class. If that figure is accurate, it suggests that fewer than 940 ROVs service all of the world's energy installations – a relatively small market to disrupt in terms of robot numbers.

The ROVs are typically used for drill support, well completion, intervention, and construction tasks. Its E-ROV and Trident models are tethered to undersea stations that are linked to communications buoys or vessels on the surface, while the Freedom ROV can also operate off-tether as an AUV. Semi-autonomous operations include obstacle avoidance, pipeline following, scouring, localisation and navigation.

Oceaneering stressed the importance of replacing the remote use of joysticks with more autonomous operations, as with nuclear decommissioning, any communications latency or human tiredness/error could have lethal consequences. It was noted that the regulation and safety aspects of autonomy remain a challenge – and therefore a commercial opportunity for specialist innovators in the field.

Meanwhile, supervising robots via screen-based point-and-click is not the ideal interface between humans and robots. Headsets, immersive environments, new data visualisation tools, and natural language communication point to a more intuitive (and less boring) future.

Oceaneering indicated that it is keen to collaborate with software specialists if there is a standard API – the company adopts a platform approach via the open source COMPAS framework. The leadership team also expressed an interest in collaboration on analytics, electric motor technologies, and trust in autonomous systems, with the latter being a cultural as well as technical barrier in the energy sector.

4.4.3 Houston Mechatronics

One of the most exciting meetings was with Houston Mechatronics[66], a 30-strong Houston start-up founded by former NASA roboticists that seeks to apply a design-led, Uber-style, on-demand service model to marine robotics. The company has developed the Aquanaut[67], a compact, self-contained AUV about the size of a hatchback car, which is capable of travelling fast underwater and then transforming into an ROV-style robot that can carry out supervised maintenance operations, via actuated arms that unfold from the machine.

In AUV mode, Aquanaut can cover up to 200km (108 nautical miles) in a single mission, while performing tasks like seabed mapping and infrastructure inspection. It transforms into a tetherless robot in a single motion to carry out advanced subsea operations "with just a few mouse clicks". In this sense, the company is selling the ability to turn an undersea valve, rather than focusing on selling the robot itself. A human operator maintains supervisory control, either onboard a support ship or sat behind a desk in an office.

The Mission met President and CEO R Matthew Ondler, Vice-President and COO Reg Berka, and Nicolas Radford, Senior Vice-President of Engineering and CTO, who would be the main contact for collaboration.

The Uber of the Sea?

At present, it can cost energy companies $125,000 a day to hire a ship, on top of which they typically need a supporting infrastructure, divers, and tethered robots – sometimes just to carry out a simple task, such as pressing a switch or turning an undersea valve. As a result, the sector is paying for inertia.

Houston Mechatronics' proposed solution is to have fleets of Aquanauts that can be summoned, Uber-style, to perform such functions quickly at lower cost. The vision is not without

[66] www.houstonmechatronics.com
[67] https://www.houstonmechatronics.com/aquanaut/

its technical challenges, however, necessitating a move from hydraulics to lighter electrical mechanisms and the development of robust command and control systems.

Another challenge is two-way communications with a tetherless undersea robot. Accordingly, the company has created a bespoke data compression/decompression algorithm for point-cloud images, allowing them to be transmitted over an acoustic modem. This enables the robot to represent complex visual/sensor information to operators from minimal data.

The company's Commander software can turn this into an immersive 3D environment for shared control of the robot – though not all delegates were impressed with the application's capabilities. Houston Mechatronics has also developed a snake robot for exploring pipes and narrow spaces and is working on a variety of land-based sensor systems.

Partnership Potential

As a boutique operation, Houston Mechatronics carries out most of its R&D in house, so partnership opportunities may be limited. However, the company has identified the North Sea as a primary market, which suggests that the UK could be a vital staging post for establishing both Aquanaut and its service-led model, if the technology proves to be both viable and safe. A partnership with Houston Mechatronics around its North Sea ambitions has game-changing potential for the UK. If nothing else, a seagoing nation with a fleet of transforming service robots is a bold message – especially if combined with the UK's plans for a new subsea engineering hub in Aberdeen.

Houston Mechatronics Aquanaut AUV

4.5 Expert Mission Engagements with Offshore Energy Sector

4.5.1 Schlumberger Robotics Services

Schlumberger[68] is the world's largest oilfield/gas services company. It employs 100,000 people and reported 2018 profits of $2.1b on revenues of $32.8b, with its biggest income coming from offshore operations. Headquartered in Houston, it also has a large European presence and maintains offices in London and a research centre in Cambridge, UK, which co-ordinates opportunities in Britain. Schlumberger has a longstanding relationship with the UK's ORCA Hub (Offshore Robotics for Certification of Assets, see below)

The Mission met Sudhir Pai, Managing Director of Schlumberger Robotics Services. (Future contacts would be via Leo Steenson, Senior Research Scientist at the Cambridge office, from where he maintains relationships with Southampton University and the NOC.)

Schlumberger spends $1b annually on R&D. In the past, the ratio was 70% hardware to 30% software, but that has now flipped: Schlumberger has become a software- and data-focused business, despite its vast engineering and hardware estate. The company acknowledged that, 10 years ago, it was looking mainly at subsurface technologies to improve traditional operations. Today, it focuses on how analytics, sensor-based insights, and AI can make its operations smoother, safer, and cleaner from gathered data. This strategic shift is combined with classical robotics.

Start-ups and research organisations are free to approach the company, if their technology maps against Schlumberger's strategic aims. It is actively looking for technologies that add value to its business, but which it may not be able to develop internally. These include AI, advanced path- and mission planning, systems that can operate in harsh or deep-sea conditions, and subsea communications in a GPS-denied environment.

In February 2019, Schlumberger announced a new joint venture, Sensia[69], with industrial automation giant Rockwell Automation. Described as "the first fully integrated digital oilfield automation solutions provider", Sensia was created to offer scalable cloud- and edge-enabled process automation to the energy sector. It is not clear whether this may lock Schlumberger into a single partner for these types of services.

In 2016, Schlumberger helped map the movement of whales and dolphins in the Southwestern Atlantic by tracking their sounds using a hydrophone towed by an autonomous Wave Glider USV[70]. The robot provided continuous data streams in a voyage of over 450 miles[71]. The company was also involved

[68] www.slb.com
[69] https://www.slb.com/news/press_releases/2019/2019-02-19-rockwell-automation-joint-venture.aspx
[70] https://www.liquid-robotics.com/wave-glider/overview/
[71] https://www.sciencedirect.com/science/article/pii/S0967063718301614?via%3Dihub

in a collaboration between Sonardyne International, Shell, and Liquid Robotics, to develop a Wave Glider that could retrieve data autonomously from sensors on the ocean floor.

4.5.2 Chevron Energy Technology

The Expert Mission delegates were hosted by John O'Brien, Research and Development Portfolio Manager for the Chevron Energy Technology Company[72] in Houston. The R&D Division takes a 20- to 30-year view of Chevron's future needs, then helps business units develop a roadmap for getting there. Earlier investments in OC Robotics[73] (an Innovate UK beneficiary, now owned by GE) came from just such an exercise.

Chevron's direct annual spend on R&D is in the region of $520m, with the R&D Division employing roughly 2,000 people worldwide and investing up to $130m a year solely in applied research – technology that has a direct line of sight into Chevron's business. Individual investments may be in the low-single-digit millions. These typically cover a one-year deliverables period, but the company's venture capital wing has greater flexibility to make multi-year deals. By contrast, O'Brien's own unit is strategic and must be fiscally neutral (it cannot make a profit or loss).

Each deal is different, but Chevron does not typically take an IP position in robotics investments, which would be seen as offering the company a non-competitive advantage. Instead, it negotiates a multi-year percentage discount on an innovator's charge-out rates, underscoring the point that it deploys robots to run its existing business more efficiently, rather than to disrupt it at its core.

With AI or ML algorithms, however, Chevron would regard the IP as a competitive differentiator, or demand an exclusive licence for a multi-year period. Alternatively, it might license a technology to a company that is better at reaching the target market and pay the inventor a royalty. In this way, it forges partnerships with players that develop new technologies, and with others that scale them.

It was noted that early Spring is the time for investment pitches, with May the deadline for discussing projects for the following calendar year. From June or July onwards, conversations would be about the year after that. Approaching his unit in the autumn would miss the strategic funding cycle.

[72] www.chevron.com/technology
[73] http://www.ocrobotics.com

5. RAI in Cross-Cutting Sectors

The Expert Mission met a number of other companies and organisations that are innovating in robotics and autonomous systems, and whose work either focuses on extreme environments or is relevant to Mission objectives in these markets. The delegates also took part in a private two-day conference, the Automation, AI, and Robotics Workshop (see below), hosted at NASA, which focused on extreme environment applications.

5.1 Expert Mission Engagements with Cross-Cutting Sectors

5.1.1 Jacobs Engineering Group

Engineering and professional services firm Jacobs[74] employs 80,000 people worldwide and generated 2018 revenues of over $15 billion. The company recently exited the chemicals and energy businesses, and focuses on aerospace, technology, and the environmental and nuclear markets. The Expert Mission visited Jacobs in Dallas and Houston, Texas.

Emphasising the links between different extreme environments, the Jacobs team explained that the building blocks of one engineering project often have applications in others, with a particular focus (for them) on nuclear robotics. Jacobs has partnered with the UK's National Centre for Nuclear Robotics (NCNR Hub)[75] in the past.

Jacobs at Clear Lake City, TX works as a prime contractor and turnkey solution provider for the NASA JSC. Jacobs contributed to the development and manufacture of the Valkyrie and Robonaut humanoids (see boxout above), along with several robotic mobility platforms.

Jacobs has developed the Autonomous Robotic Gravity Offload System (ARGOS)[76] for NASA– a robotic gantry that can simulate weightless conditions on Earth, offering benefits not only in astronaut training, but also in medical rehabilitation. There may be long-term potential for such a system to work in radioactive hot cells in the nuclear industry.

Other robotics projects undertaken by Jacobs include sensor-filled sphere and snake robots that can examine pipes and narrow spaces – the former for Shell, and the latter for NASA – and robots that can swim inside contaminated tanks in the nuclear sector. In each case, the robot allows humans to monitor facilities in extreme environments that would be impossible to access in any other way. This negates the need for humans to disassemble complex systems to trace the cause of problems.

Partnership Opportunities

Among the Jacobs representatives, the Mission met Brian Harvie, External Pursuits Program Manager – the first point of contact for future collaborations – and David A Kerr, Senior Speciality Engineer and Project Manager.

Jacobs has been tasked by NASA and the US government with finding new academic and commercial partners to use the space agency's facilities and bring in new business. In this way, deals could be made with Jacobs across the full spectrum of engineering disciplines, without signing a Space Act Agreement with NASA itself – thanks to Jacobs' longstanding relationship developing spacecraft systems for the JSC. This could offer a potential gateway for UK start-ups, blue-chips, and academic institutions to forge indirect relationships in the US space programme, project-managed by Jacobs. Those deals would need to be made sooner, rather than later, as the JSC and Jacobs gear up for the lunar missions.

It was also highlighted that NASA plans to launch an open robotics competition for universities and commercial partners to help design teams of robots that collaborate autonomously in remote locations. The UK should follow this up as soon as details are announced.

5.1.2 Southwest Research Institute (SwRI)

The Southwest Research Institute (SwRI)[77] at San Antonio, TX, is an independent non-profit organisation focused on applied R&D for commercial and government clients, driven by customers' need to modernise their industries. The Expert Mission met Maria Araujo, R&D Manager of the Critical Systems Department of the Intelligent Systems Division, which is primarily engaged in automation, industrial robotics, and advanced inspection systems.

The SwRI has nine other divisions with domain expertise: Applied Physics; Applied Power; Chemistry & Chemical Engineering; Defence & Intelligence Solutions; Fuel & Lubricants Research; Mechanical Engineering; Nuclear Waste Regulation; Powertrain Engineering; and Space Science & Engineering. These map well against the UK's Industrial Strategy, and the organisation could be a model to emulate in terms of its structure and purpose – an on-demand think-tank and technology developer with industrial domain expertise.

[74] www.jacobs.com
[75] https://www.ncnr.org.uk
[76] https://www.nasa.gov/centers/johnson/engineering/integrated_environments/active_response_gravity/
[77] www.swri.org

While SwRI can take concepts all the way from Technology Readiness Level (TRL) 1 (basic research) to TRL 9 (systems test launch and operation), its 'sweet spot' is typically TRLs 3-7 (feasibility to demonstration). The client usually retains the IP, with SwRI working in a brains-trust capacity. As a non-profit, however, the organisation is not able to endorse technologies.

One major area of client work is in the oil and gas sector, where SwRI has helped to automate the inspection of pipelines and reduce methane emissions – for example, via UAVs fitted with sensors and infrared cameras. In these instances, SwRI appears to be adapting off-the-shelf products and writing AI or ML algorithms, rather than partnering with robotics developers on bespoke solutions. Analytics is typically carried out at the edge, placing such applications firmly in an Industrial IoT (IIoT) space.

However, with its breadth of service and its unusual position as a well-resourced solutions finder, SwRI offers partnership potential and could be a platform for raising a start-up's US visibility to industrial companies.

The ROS-Industrial Consortium

The Expert Mission delegates also met Matt Robinson, SwRI's Programme Manager in the Intelligent Systems Division, who serves as Chair of the ROS-Industrial Consortium that promotes the open source Robot Operating System (ROS). The aim is to establish greater interoperability between industrial robots and create a shared development platform. Global members include Airbus, BMW, Boeing, Bosch, CAT, Fraunhofer, Microsoft, NIST, Siemens and numerous robotics specialists, including Blue Ocean, Open Robotics, Tony Robotics and Universal Robotics.

ROS stood out as one of the most pervasive development tools in robotics, and as a potent collaboration platform. ROS is popular in both academia and industry, as demonstrated by several presentations at the two-day Robotics and AI Workshop at NASA JSC. Open source ROS libraries allow developers to build on each other's work without replicating effort. More, they enable experts in one area to access algorithms and tools in another, encouraging the cross-fertilisation of ideas.

5.1.3 Brain Corp

In San Diego, the Mission met a company with a similar service-led approach to Houston Mechatronics. AI-for-service-robotics company Brain Corp[79] doesn't work in extreme environments, but its technology and business model could be adapted for them.

The industrial robotics market is predicted to grow at a compound annual growth rate (CAGR) of 25% to 2027. In that space, Brain specialises in Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs), with the latter offering the biggest forecast growth opportunity – 53.4%, according to ABI Research, which ranks Brain Corp as the No 1 autonomy service provider.

Brain Corp behaves like a product company, but without being one. It focuses on AI and sensors for safe robot navigation in complex, dynamic spaces, and on seamless integration with industrial processes. This links it with extreme environments – where marine robotics providers also face navigation challenges – and with mainstream autonomous transport developers.

The Mission met Phil Duffy, VP of Innovation. As a company with a specialist AI focus – gathering data from factory and warehouse environments to improve navigation capabilities – Brain Corp offers partnership potential and could be a valuable source of commercial advice. Delegates were inspired by Brain's clear commercial vision, suggesting that the market is crying out for persuasive messages about problem-solving, service, and business value. From this perspective, Brain Corp and Houston Mechatronics stood out from other Mission visits.

5.1.4 US Army Research Laboratory (ARL)

The Mission attended a series of presentations at the US Army Research Laboratory (ARL)[80] in Los Angeles, its central R&D centre. This forms part of a strategic 'open campus' initiative to expose the armed forces to innovations from the private and academic sectors, including the US' 50+ engineering-focused universities. Much US Army research is now privately funded, according to speakers at the facility.

Among the initiatives run by the lab is the Robotics Collaborative Technology Alliance (RCTA)[81]. Participants in this include NASA JPL, General Dynamics, Florida State University, University of Pennsylvania, Massachusetts Institute of Technology (MIT), Carnegie Mellon Robotics Institute, UCF and Qinetiq North America. The RCTA is researching ways to team foot soldiers with autonomous robotics, ranging from microsystems and exoskeletons to UAVs and unmanned vehicles. The aim is to give troops better situational insights – not just on the battlefield, but also in disaster zones, bomb disposal situations, and route-clearance missions. As with other extreme environments, time may be critical, radio communications difficult, GPS denied, and navigation complex.

The Reasoning Robot

The ARL is researching intelligent systems that understand the environment, learn from experience, adapt to dynamic

[78] www.rosindustrial.org
[79] www.braincorp.com
[80] www.arl.army.mil
[81] https://www.arl.army.mil/www/pages/392/RCTA-Website-Overview-Briefing-v2.pdf

situations, possess “a common world view”, communicate naturally, perform useful functions, and act independently “within well-prescribed bounds”. The Lab wants soldiers to be able to communicate with robots swiftly and intuitively, via speech recognition and natural language processing, not via onscreen point and click[82]. Accordingly, it is also advancing RAI systems’ capacity for abstract reasoning, learning by example, reinforcement learning, semantic perception, human behaviour modelling, manipulation and agile 3D mobility.

The ARL demonstrated an immersive AR environment in which remote operators blend real-time data from drones and ground robots to give soldiers a virtual picture of the battlefield to create life-saving systems for troops whilst also conferring a tactical advantage.

The UK Perspective

UK armed forces are exploring similar approaches. Last year, the SAPIENT[83] system (Sensors for Asset Protection using Integrated Electronic Network Technology) was tested in mock-battle. The AI-powered system was developed by the Defence Science and Technology Laboratory (DSTL)[84] and industry partners, originally co-funded by Innovate UK. Under the Autonomous Warrior[85] initiative, a range of prototype unmanned aerial and ground-based vehicles were also tested by the DSTL for reconnaissance and supply-line duties.

Other ARL presentations included:

1. New AI chip architectures
   ARL designs chips for the Army AI Innovation Institute (A2I2)[86]. As chip architectures move across the spectrum from CPUs (central processing units) to FPGAs (field-programmable gate arrays) to ASICs (application-specific integrated circuits), they become simpler and more efficient, but generally less flexible. The ARL is developing FPNA (field-programmable neural arrays) chips that are more flexible than ASICs, and sophisticated enough to perform AI and ML tasks at low power. This is part of a wider trend in AI, IoT, edge, and mobile systems research towards developing lightweight, low-power architectures for inference tasks. As such, it represents a significant commercial opportunity.

2. Virtual realism
   An AR start-up Pinscreen[87] explores the interface between AI and hyper-realistic avatars. The aim is to create immersive, photo-realistic communication platforms using deep-learning-based facial synthesis. In other words, the more realistic and ‘human’ virtual characters appear, the more people will be willing to communicate via them – without the ‘uncanny valley’ problem that afflicts CGI characters. Aspects of this research were funded by the ARL.

5.1.5 The Automation, AI and Robotics Workshop

In Houston, the Expert Mission attended a two-day RAI conference at the NASA JSC. The Automation, AI and Robotics Workshop on 26-27 March 2019 was run by the Technology Collaboration Center (TCC)[88], a member-driven non-profit organisation seeking to develop interdisciplinary approaches to real-world problems.

The Workshop brought together many of the West’s leading academics, researchers, business leaders and start-ups in robotics and AI, with most sessions focusing on the technology challenges of extreme environments, underlining how robotics and AI are becoming synonymous with these applications.

US speakers included representatives from: the NASA JSC, imec[89], the Universities of Colorado[90], Houston[91], Central Florida[92], Nebraska Omaha[93] and Texas[94], Rice University[95], South West Research Institute, Schlumberger, Jacobs, Houston Mechatronics, TRACLabs[96], Ecolab[97] and the Electric Power Research Institute (EPRI)[98].

[82] https://www.arl.army.mil/arlreports/2015/ARL-TR-7443.pdf
[83] https://internetofbusiness.com/cue-weaponised-a-i-as-autonomous-uk-tech-shines-on-battlefield/
[84] https://www.gov.uk/government/organisations/defence-science-and-technology-laboratory
[85] https://www.army.mod.uk/news-and-events/events/awe-2018/
[86] https://www.army.mil/article/211285/arls_research_with_a_difference
[87] https://pinscreen.com/
[88] https://techcollaboration.center/
[89] https://www.imec-int.com/en/home
[90] https://www.colorado.edu
[91] http://www.uh.edu
[92] https://www.ucf.edu
[93] https://www.unomaha.edu
[94] https://www.utexas.edu
[95] https://www.rice.edu
[96] https://traclabs.com
[97] https://en-uk.ecolab.com
[98] https://www.epri.com

The UK's presence at the event was significant. Shadow Robot Company[99] gave a presentation that positioned the firm's robot hands in the vanguard of research in this area. There were also a dozen senior speakers from the UK's four academic Robotics Hubs of National Hub on Future AI & Robotics for Space (FAIR-SPACE)[100], National Centre for Nuclear Robotics (NCNR)[101], Robotics & AI for Nuclear Hub (RAIN)[102] and Offshore Robotics for Certification of Assets Hub (ORCA)[103].

Individual presentations and panel discussions revealed a RAI industry that is forging strong research and commercial bonds, both within and between the US and UK. However, it was noticeable that some organisations are working on solving the same engineering problems discretely – duplicating efforts in pursuit of competing solutions. This is a commercial reality for any IP-focused enterprises

[99] https://www.shadowrobot.com
[100] https://www.fairspacehub.org/
[101] https://www.ncnr.org.uk/
[102] https://rainhub.org.uk/
[103] https://orcahub.org/

Annex 1

List of UK Participants

Autonomous Devices (www.autonomousdevices.co.uk)

Brunel Innovation Centre (www.brunel.ac.uk/bic)

ORCA Hub Heriot-Watt University (https://orcahub.org)

D-RISQ (www.drisq.com)

Forth Engineering (Cumbria) Ltd. (www.forth.uk.com)

Headlight AI (www.headlight.ai)

Hybird (www.hybirdtech.com)

London South Bank Innovation Centre for Mobile Robotics (LSBIC) (www.lsbu.ac.uk/schools/engineering/research/london-south-bank-innovation-centre)

Rolls-Royce (www.rolls-royce.com)

Royal Holloway University of London (RHUL). (www.cs.rhul.ac.uk)

Shadow Robot (www.shadowrobot.com)

Soil Machine Dynamics Ltd. (www.smd.co.uk)

Innovate UK. (www.gov.uk/government/organisations/innovate-uk)

Knowledge Transfer Network. (www.ktn-uk.org)

UK Science and Innovation Network (www.gov.uk/world/organisations/uk-science-and-innovation-network) ktn