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FOREWORD

SPACE ROBOTICS AND AUTONOMOUS SYSTEMS

Welcome to the UK-RAS White Paper Series on Robotics and Autonomous Systems (RAS). This is one of the core activities of UK-RAS Network, funded by the Engineering and Physical Sciences Research Council (EPSRC). By bringing together academic centres of excellence, industry, government, funding bodies and charities, the Network provides academic leadership, expands collaboration with industry while integrating and coordinating activities at the EPSRC funded RAS capital facilities, Centres for Doctoral Training and partner universities.
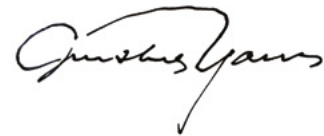
In this white paper, a comprehensive overview of space RAS is provided, covering historical developments and technological evolution over the years. The UK has extensive expertise and facilities in space RAS. Our ambition to explore and ultimately to work and live in space are major drivers of the sector. The technologies developed in space RAS are major enablers to a wide range of manned and unmanned space missions. Space RAS is unique, sharing many common challenges with terrestrial RAS yet facing distinctive design and environment constraints. I hope the vision and technical roadmap outlined by the authors will inspire future research, promote collaboration, and identify key areas of future growth in this fascinating area of RAS.

The UK-RAS white papers are intended to serve as a basis for discussing the future technological roadmaps, engaging the wider community and stakeholders, as well as policy makers in assessing the potential social, economic and ethical/legal impact of RAS. It is our plan to provide annual updates for these white papers so your feedback is essential - whether it be pointing out inadvertent omission of specific areas of development that need to be covered, or major future trends that deserve further debate and in-depth analysis.

Please direct all your feedback to white-paper@ukras.org. We look forward to hearing from you!

Prof Guang-Zhong Yang, FREng
Chair, UK-RAS Network

Yang Gao
Professor of Space Autonomous Systems, Head of STAR Lab, University of Surrey.

Daniel Jones
Space Robotics SRC - UK Lead, UK Space Agency.

Roger Ward
Technology Manger, Space Division, SciSys Ltd.

Elie Allouis
Robotics and Mission Systems Engineer, Future Programmes, Airbus Defence and Space Ltd.
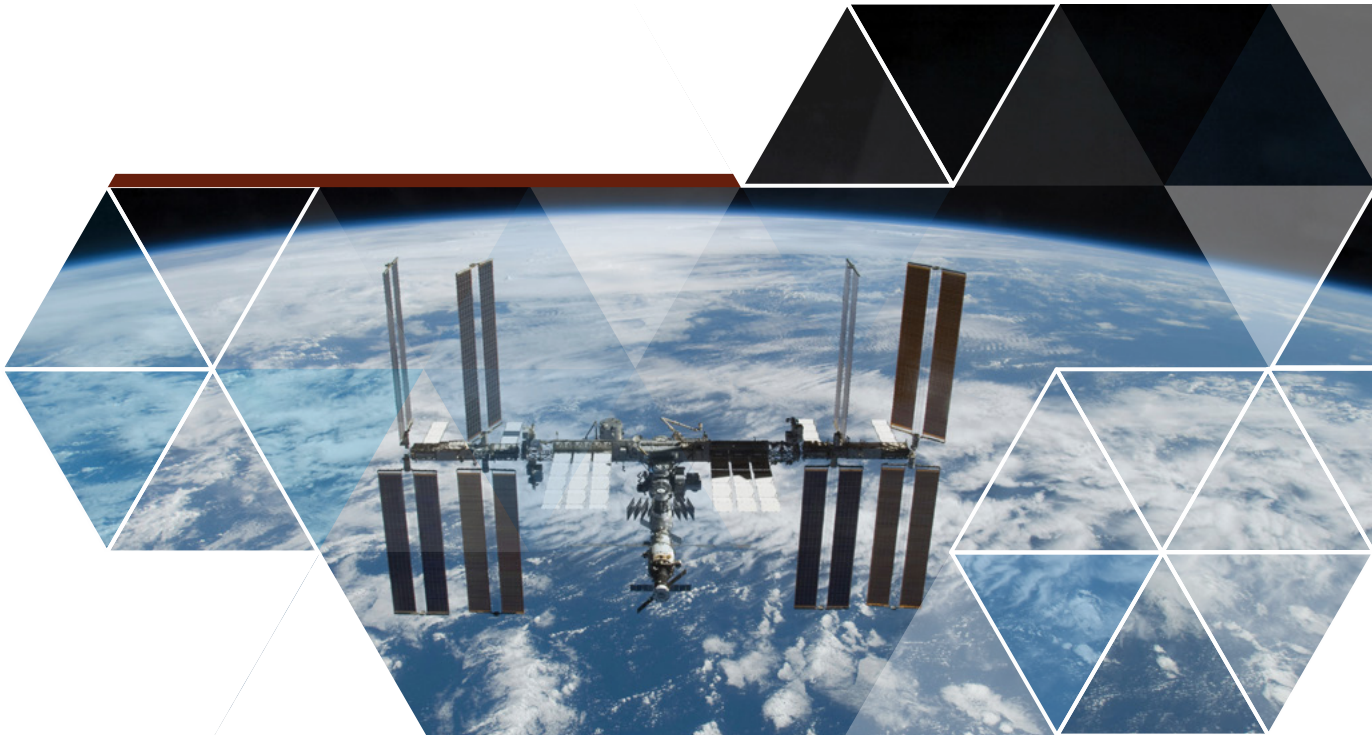
Aron Kisdi
Robotics Systems Engineer, Autonomous Systems Group, RAL Space, STFC.

on behalf of the UK-RAS Network, established to provide academic leadership, expand collaboration with industry while integrating and coordinating activities at EPSRC funded RAS capital facilities, Centres for Doctoral Training and partner universities.

CONTENTS

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Robotics already plays a key role in space exploration and exploitation, supporting both manned and un-manned missions. When coupled with increasingly capable autonomous and intelligent systems, robotics will enable yet more audacious exploration of our solar system whilst also reducing the cost and increasing the use of space to manage our Earth's resources and monitor our environment.

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Professor Sir Martin Sweeting
Executive Chair, SSTL

1. INTRODUCTION

Space robotics and autonomous systems (or Space RAS) play a critical role in the current and future development of mission-defined machines that are capable of surviving in the space environment, and performing exploration, assembly, construction, maintenance, or servicing tasks. Modern space RAS represents a multi-disciplinary emerging field that builds on as well as contribute to knowledge of the space engineering, terrestrial robotics, computer science as well as many miscellaneous subjects like materials and IT.

Space RAS are important to human's overall ability to explore or operate in space, by providing greater access beyond human spaceflight limitations in the harsh environment of space and by providing greater operational handling that extends astronauts' capabilities. Autonomous systems are capable of reducing the cognitive load on humans given the abundance of information that has to be reasoned upon in a timely fashion, hence are critical for improving human and systems' safety. RAS can also enable the deployment and operation of multiple assets without the same order of magnitude increase in ground support. Given the potential reduction to the cost and risk of spaceflight both manned and robotic, space RAS are deemed relevant across all mission phases such as development, flight system production, launch and operation.

Space RAS covers all types of robotics for the exploration of a planet surface as well as robotics used in orbit around the Earth and the sensors needed by the platform for navigation or control. Orbital robots can be envisaged for repairing satellites, assembling large space telescopes, capturing and returning asteroids, or deploying assets for scientific investigations, etc. Planetary robots play a key role in the surveying, observation, extraction, close examination of
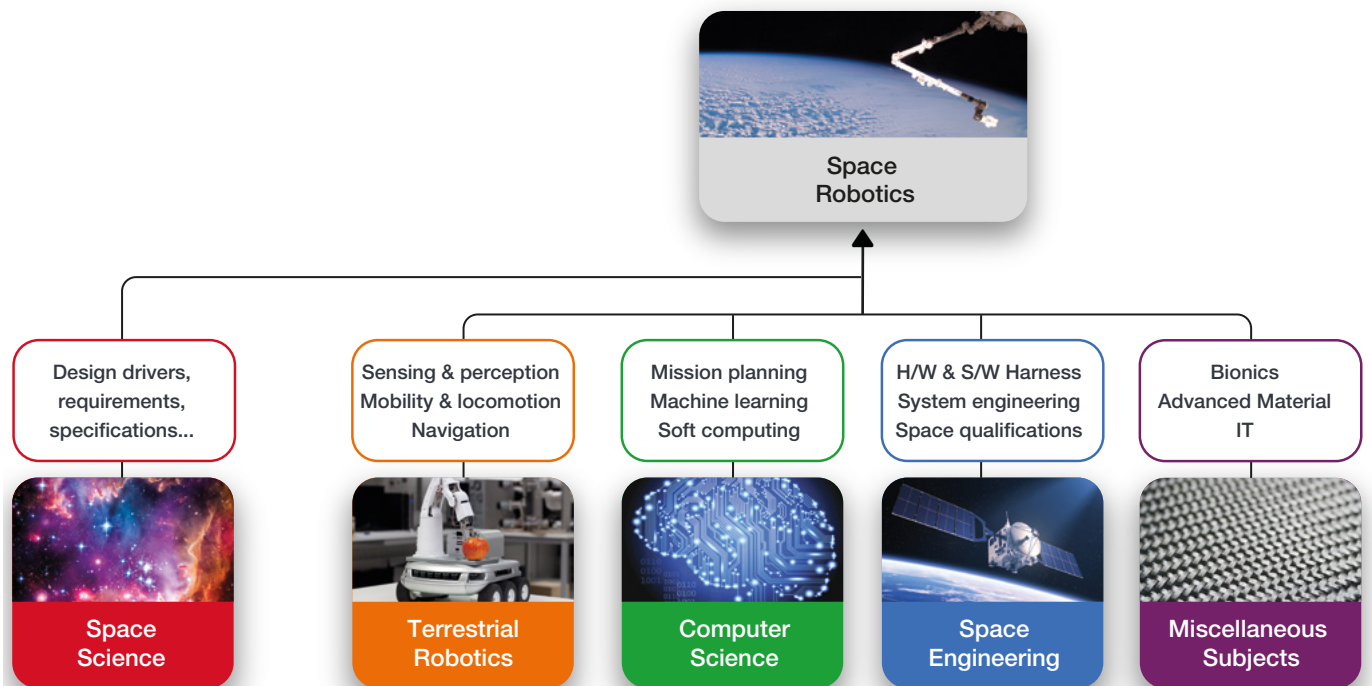

	Space Robotics			
Design drivers, requirements, specifications...	Sensing & perception Mobility & locomotion Navigation	Mission planning Machine learning Soft computing	H/W & S/W Harness System engineering Space qualifications	Bionics Advanced Material IT
Space Science	Terrestrial Robotics	Computer Science	Space Engineering	Miscellaneous Subjects

FIGURE 1.

Space RAS, a multi-disciplinary emerging field

extra-terrestrial surfaces (incl. natural phenomena, terrain composition and resources), constructing infrastructures on a planetary surface for subsequent human arrival, or mining planetary resources, etc.

Depending on these applications (either orbital or planetary), space robots are often designed to possess mobility (or locomotion) to manipulate, grip, rove, drill and/or sample. Driven similarly by the nature of the mission and distance from the Earth, these robots are expected to possess varying level of autonomy, ranging from tele-operation by human to fully autonomous operation by the robots themselves[1]. Depending on the level of autonomy, a space robot can act as 1) a robotic agent (or human proxy) in space to perform various tasks using tele-operation up to semi-autonomous operation, or 2) a robotic assistant that can help human astronauts to perform tasks quickly and safely, with higher quality and cost efficiency using semi to fully autonomous operation, or 3) a robotic explorer that is capable of exploring unknown territory in space using fully autonomous operation.

[1] Level of autonomy onboard spacecraft defined by European Cooperation for Space Standardization (ECSS):
Level E1: execution mainly under real-time ground control, i.e. remote or tele-operation.
Level E2: execution of pre-planned mission operations onboard, i.e. automatic operation.
Level E3: execution of adaptive mission operations onboard, i.e. semi-autonomous operation.
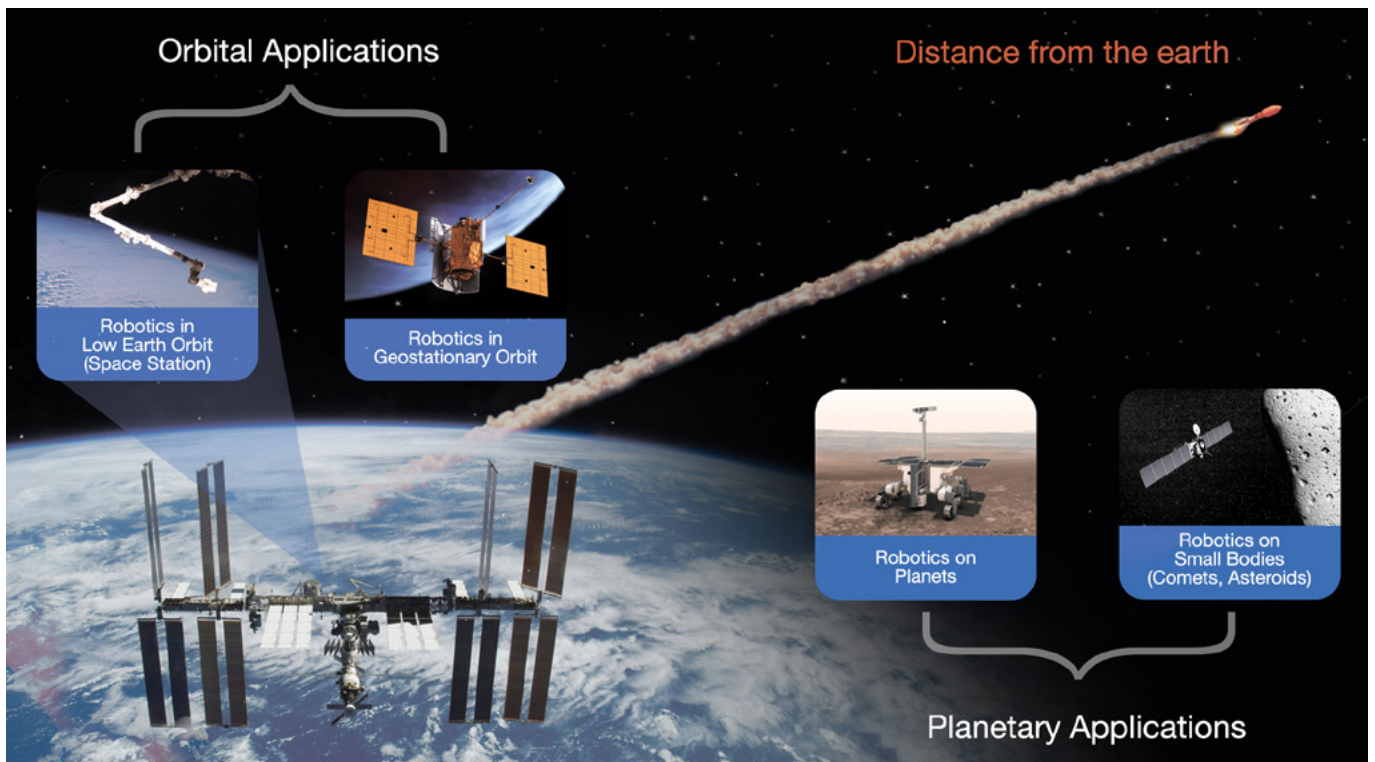Level E4: execution of goal-oriented mission operations onboard, i.e. fully autonomous operation.

FIGURE 2.

Applications of space RAS, from orbital to planetary.

2. HISTORY AND TECHNOLOGY EVOLUTION

The need for humans to explore beyond the realm of the Earth is driven by our inherent curiosity. Throughout our history, new world has been discovered by daring explorers who set out to discover new lands, find riches or better understand these little-known territories. These journeys were fuelled by the technological advances of the times such as the compass, maritime maps or plane, and in return contributed tremendously to the scientific knowledge of humankind.

Outer space has provided real, new exploration frontiers for mankind since the 1950s. With the capability and the irresistible attraction to go beyond our planet Earth, minimizing the impact of mankind on other extra-terrestrial bodies (be it a planet, a moon, a comet or an asteroid) is paramount. The onset of space exploration in the late 1950s to early 1960s focused on sending humans into the Earth orbit and the Moon as a result of the space race between the USSR and USA. In parallel to the expensive development of manned space programs, the use of cheaper robotic proxies was critical to understand the space environment where the astronauts would be operating as well as to further explore our solar system.

Across the existing robotic missions, a range of mobility or locomotion systems has played a significant role, including the surface rovers, robotic arms or manipulators, subsurface samplers and drills. Table 1 summarizes the missions and robots successfully flown on Earth orbit, the Moon, Mars, and small bodies.

The first genuine robotic mobility system successfully operated on an extra-terrestrial body was a scoop (i.e., a manipulation cum sampling device) onboard the Surveyor 3 lander launched in 1967 to the Moon. Following that, Luna 16 succeeded with the first planetary robotic arm-mounted

Year	Mission	Country	Target	Rover	Arm	Sampler	Drill
1967	Surveyor 3	USA	Moon			x	
1970/72/76	Luna 16/20/24	USSR	Moon		x	x	x
1970/73	Luna 17/21	USSR	Moon	x			
1975	Viking	USA	Mars		x	x	
1981/2001/08	ISS's Canadarm1/2/Dextre	Canada	Earth orbit		x		
1996	Mars Path Finder	USA	Mars	x			
2003	Hayabusa	Japan	Asteroid			x	
2003	Mars Exploration Rovers	USA	Mars	x	x	x	
2007	ISS's Kibo	Japan	Earth orbit		x		
2008	Phoenix	USA	Mars		x	x	
2011	Mars Science Laboratory	USA	Mars	x	x	x	
2013	Chang'E 3	China	Moon	x			
2004-14	Rosetta	Europe	Comet		x	x	x

TABLE 1.

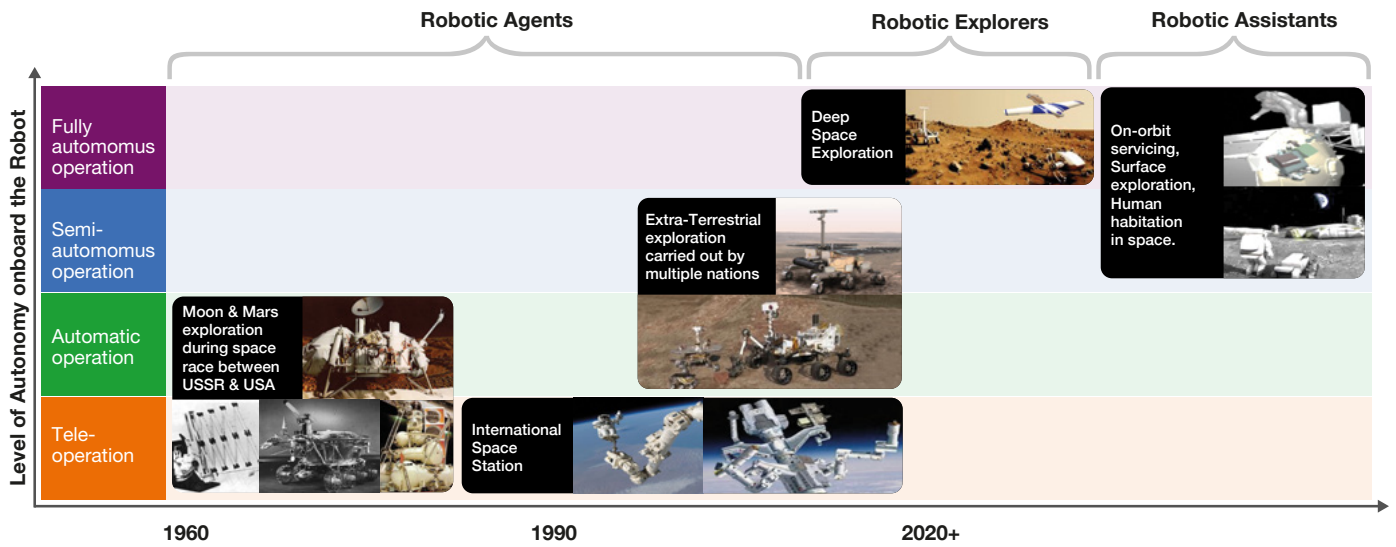Successfully flown robots on Earth orbit, the Moon, Mars, and small bodies as of 2016.

FIGURE 3.

Evolution and roadmap of space RAS in terms of level of onboard autonomy.

drill in 1970, and Luna 17 succeeded with the first planetary rover called Lunokhod 1 in 1970. These "firsts" led to incredible mission successes and science discoveries as a result of unabated and relentless launch attempts during the space race between the superpowers.

Building on these foundations since the 1990s, the new generation of planetary exploration has travelled further into the solar system and is anticipated to require an increased level of autonomy (see Figure 3). Most existing, successfully flown space robots are considered robotic agents that act as human proxies in space. As time progresses, future space missions with increasingly challenging goals will require higher level of autonomy onboard the robots, leading to an evolution towards robotic explorers and robotic assistants. It is envisaged that RAS will continue to change the way space is explored in even more fundamental ways, impacting both human and science exploration.

3. TECHNICAL GOALS AND CHALLENGES

The current desire to go and explore space is as strong as ever. Past space powers have been gradually joined by a flurry of new nations eager to test and demonstrate their technologies and contribute to an increasing body of knowledge. Commercial endeavours also have eyes on space and actively promote the Moon and Mars as possible destinations for long-term human presence or habitation. Shall the future exploration missions be manned or unmanned, space robots are always desired to deliver the robotic "avatars" and perform in situ tasks to proxy, assist or explore through their "eyes", "ears", "noses" and "hands."

In particular, the technical goals of RAS are to extend human's reach or access into space, expand our abilities to manipulate assets and resources, prepare them for human arrival, support human crews in their space operations, support the assets they leave behind, and enhance efficiencies of mission operations across the board. Advances in robotic sensing and perception, mobility and manipulation, rendezvous and docking, onboard and ground-based autonomous capabilities, and human-robot integration will drive these goals.

NASA in its latest 2015's technology roadmap has identified several RAS areas needed by 2035. Similarly, ESA has been developing technology roadmaps in RAS through various European Commission funded projects such as PERASPERA and SpacePlan2020. Other space fairing nations like Russian, China, India and Japan have also announced their individual plans on future missions involving space RAS. Besides difference in mission timetable by different space players, there are quite a number of technological needs or challenges in RAS that are widely acknowledged by the international space community (see Table 2).

Areas	Goals	Technological Needs or Challenges
Sensing & perception	To provide situational awareness for space robotic agents, explorers and assistants.	New sensors; Sensing techniques; Algorithms for 3D perception, state estimation and data fusion; Onboard data processing and generic software framework; Object, event or activity recognition.
Mobility	To reach and operate at sites of scientific interest on extra-terrestrial surfaces or free space environments.	Mobility on, into, and above an extra-terrestrial surface using locomotion like flying, walking, climbing, rappelling, tunnelling, swimming and sailing; Manipulations to make intentional changes in the environment or objects using locomotion like placing, assembling, digging, trenching, drilling, sampling, grappling and berthing.
High-level autonomy for system and sub-systems	To provide robust and safe autonomous navigation, rendezvous and docking capabilities and to enable extended-duration operations without human interventions to improve overall performance of human and robotic missions.	Guidance, navigation and control (GNC) algorithms; Docking and capture mechanisms and interfaces; Planning, scheduling & common autonomy software framework; Multi-agent coordination; Reconfigurable and adjustable autonomy; Automated data analysis for decision making.
Human-robot interaction	To enable human to accurately and rapidly understand the state of the robot in collaboration and act effectively and efficiently towards the goal state.	Multi-modal interaction; Remote and supervised control; Proximate interaction; Distributed collaboration and coordination; Common human-system interfaces.
System engineering	To provide a framework for understanding and coordinating the complex interactions of robots and achieving the desired system requirements.	Modularity, commonality and interfaces; Verification and validation of complex adaptive systems; Robot modelling and simulation; Software architectures and frameworks; Safety and trust.

TABLE 2.

Technological needs and challenges for space RAS in the coming decades.

4. UK STRENGTHS & CAPABILITIES

4.1 TECHNOLOGIES

Within the space sector, the UK industry is considered to be at the forefront of RAS technologies. The UK is the largest contributor to the ESA ExoMars programme and is currently prime for the ExoMars rover vehicle as well as being responsible for a number of key autonomy related subsystems such as the vision based GNC software as well as the mission management software. In addition, UK companies have won ESA studies looking ahead at future mission concepts to the Moon, Mars, and beyond, focusing on the next major milestone in planetary exploration (i.e. a sample return mission). To this end, the UK leads and contributes to the development of a range of mission concepts including the Lunar Polar Sample Return mission or the Phobos Sample Return mission as a precursor to a Mars Sample Return implementation. The UK space industry also targets the development of those key underlying technologies as shown in Table 2 through robotic platforms like rovers, robotic arms and sampling systems offering different level of autonomy.

The UK is also home to a well-established R&D community of universities and small businesses that is world-renowned in RAS capabilities for space. This community is actively involved in advancing space RAS in collaboration with UK industrial partners through national and international research programs, covering topics in system autonomy and modelling, vision-based GNC, robot-soil interaction and biomimetic mechanism that underpin major technology advancement applicable to both the orbital and planetary robotic platforms. Some examples include the visual odometry technique already used by the ExoMars rover, the advanced planetary monocular SLAM (PM-SLAM) technique, the camera/LIDAR data fusion technique, or the novel soil characterization and drilling techniques for next-generation robotic systems applicable to Mars/Phobos sample return missions.
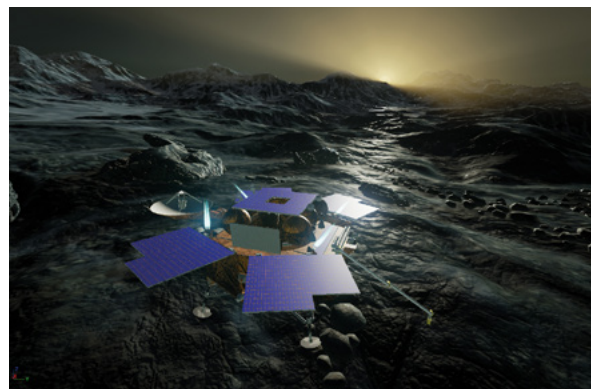

FIGURE 4:

(Top) -ExoMars Rover [Courtesy ESA];
(Bottom) - Phobos Sample Return mission
[Courtesy Airbus DS Ltd]

Looking forward to the next decade, the UK National Space Technology Program (NSTP) has identified or prioritized tens of individual technologies in relation to space RAS and grouped them into several research themes:

- Autonomous/Intelligent Vehicles, including autonomous mission management, science autonomy, robotic control, navigation or localisation without GPS, data fusion and multi-agent autonomy.
- Robotic Manipulators, including tele-operation, sampling devices, sample transfer and manipulation, rendezvous and docking.
- Penetrators, including modelling of de-orbit, entry and descent, flight control of high velocity objects, sensors.
- Novel Locomotion Platforms, including aerobots, climbing robots.
- Robotic Support of Manned Exploration, including human factors, multi-agent collaboration, in-situ resource utilisation.

4.2 TEST FACILITIES

The UK offers a number of unique facilities belonging to the government, industry or academia to help support R&D of space RAS and establish UK's strengths/priorities in relevant fields. A few complementary examples are provided below.
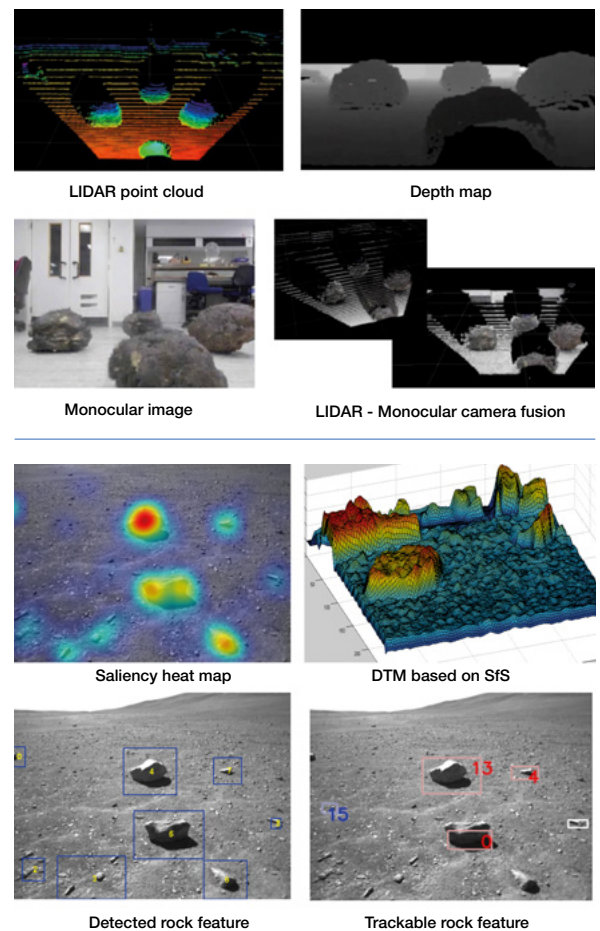

LIDAR point cloud   Depth map

Monocular image   LIDAR - Monocular camera fusion

Saliency heat map   DTM based on SfS

Detected rock feature   Trackable rock feature

FIGURE 5:

Advanced R&D on cognitive vision, machine learning, and multi-sensory data fusion enabling next-generation sample return rovers [Courtesy University of Surrey]

4.2.1   AIRBUS MARS YARD

As part of the ExoMars development, Airbus DS Ltd has built a fully featured indoor test facility, - the Mars Yard - that allows the extensive testing of full size rover prototypes in suitably representative conditions. The 13m by 30m facility includes a large test area overlooked by a control room. The testing area features 300 tons of sand with a colour visually representative of the expected Martian soil, ambient lighting with a temperature and intensity typical of a Martian day, and an indoor positioning system to provide the require position ground truth for the platforms under test. The Mars Yard has been extensively used to test RAS technologies on three Airbus DS rover prototypes developed for missions like ExoMars and R&D projects in collaboration with university and business partners.
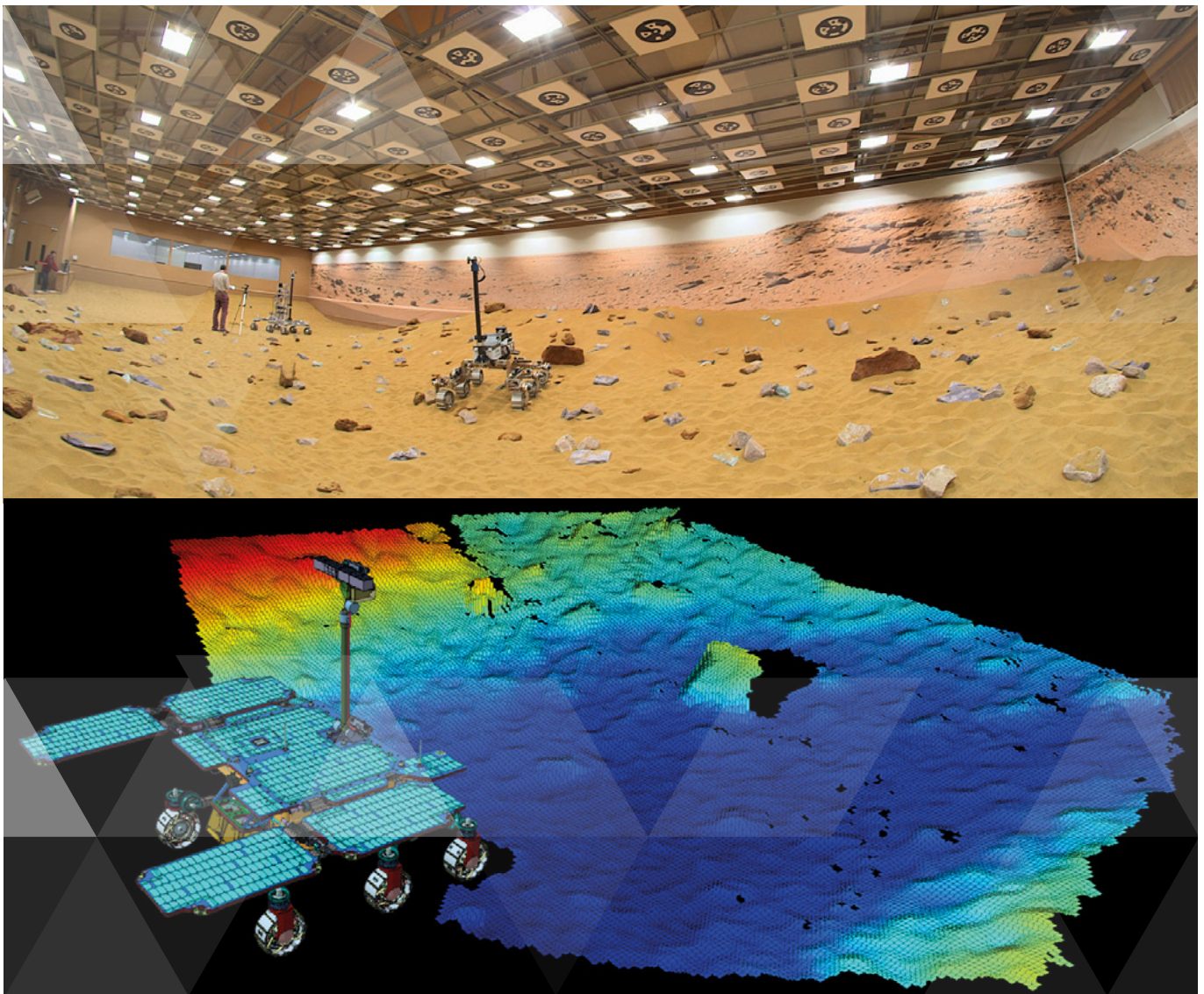

FIGURE 6:

Mars Yard - A little piece of Mars in the UK [Courtesy Airbus DS Ltd]

4.2.2 HARWELL ROBOTICS AND AUTONOMY FACILITY (HRAF)

The UK has taken the lead in addressing the question of validation of autonomous space systems through the HRAF funded by both ESA and UKSA. This programme has been defining technologies and processes needed to validate typical space systems but also working with other sectors to exploit common issues through sharing of expertise and investment. The facility can support virtual validation of missions, gathering and archiving data from field trials to help validate technologies as well as a support unit to do the logistics and safety aspects of field trials in remote places like the Atacama dessert.

4.2.3 STFC BOULBY UNDERGROUND LABORATORY

Boulby Mine is a working potash and rock-salt mine in the north-east of England that has been operational since 1973. As well as mining, processing and exporting potash, polyhalite and salt, the mine is home to the Palmer Lab, a fully equipped underground laboratory over 1100m beneath the surface of the Earth, which provides a shield against cosmic rays over a million times stronger than on the surface. The lab itself provides clean, contamination-free lab space, and 1 million times more protection against cosmic rays than labs on the Earth's surface, hence has been used to test space borne instruments such as ExoMars PanCam and Raman spectrometer, etc.

4.2.4 SURREY'S PLANETARY SOIL SIMULANTS PREPARATION, CHARACTERIZATION & TESTING FACILITY

The University of Surrey's STAR Lab offers planetary soil (dry and icy) preparation techniques and equipment for testing and characterization relevant simulants' physical properties. The facility includes various test rigs for studying robot-soil interaction and analysing soil traversability or penetration for a wide range of robotic mobility or locomotion systems covering rovers (wheeled, legged and tracked), drills and samplers. The test environment also provides force control, adjustable gravity effect, and automated data acquisition and analysis.

FIGURE 7:

Validation of rover long-range navigation technology using virtual facility (Top) and physical facility at Atacama Desert (Bottom [Courtesy SCISYS]
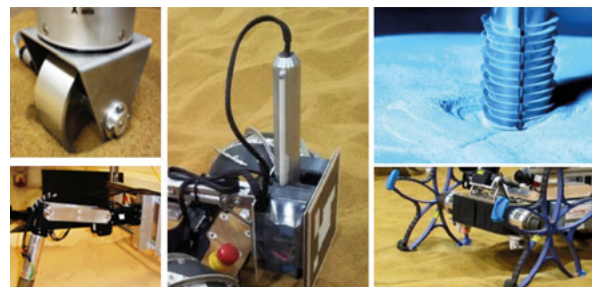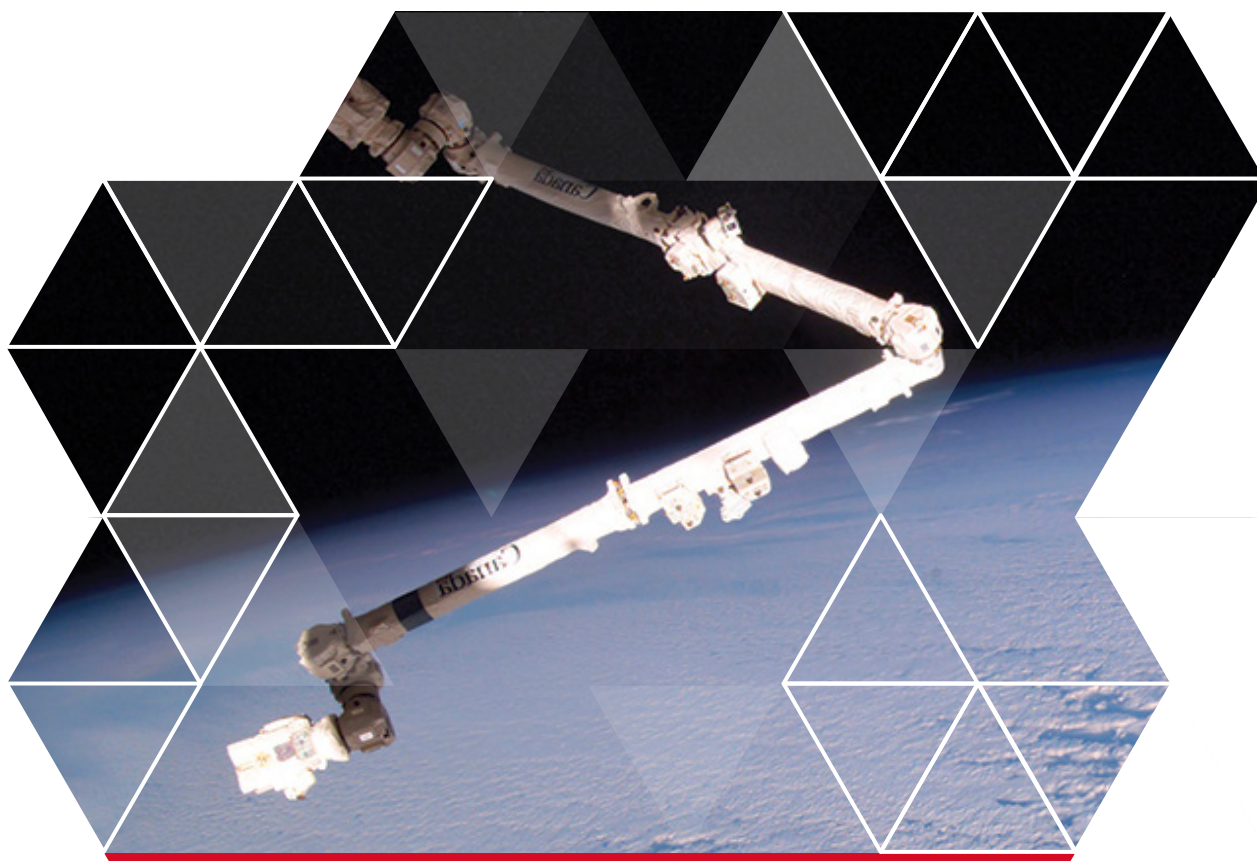

FIGURE 8:

State-of-the-art R&D on planetary robot-soil interaction [Courtesy University of Surrey]

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Space literally takes robotics to other worlds, and the UK's skills and technology for robotics are paving the way for new science and business.

"

Dr. Ralph Cordey, Head of Science,
Airbus Defence and Space Ltd.

5. OPPORTUNITIES & BENEFITS

5.1 FUTURE SPACE MISSIONS

- **ExoMars Phase 2:** Presently ExoMars is the only European funded mission to make substantial use of RAS in the form of an autonomous rover, an automated exobiology laboratory and robotised drilling system, due to be launched in 2020 to complement the ExoMars phase 1 launched in March 2016. The spacecraft of the mission is being developed by industries from over 20 countries where UK has several industrial and academic organizations contributing.

- **Mars Sample Return (MSR):** The ESA SRE Directorate has been for some time elaborating on a joint ESA-NASA Mars Exploration programme that would send missions to Mars at any opposition, with the final aim of performing a joint Mars Sample Return (MSR) mission. One of the concepts that are currently studied in the context of the MSR preparation is the ESA Sample Fetching Rover (SFR), which envisages the development of a small platform with very high traverse requirement (in the order of 15km), in order to fetch cached samples back to the Mars Ascent Vehicle (MAV). The mission has been addressed by a first ESA Concurrent Design Facility (CDF) study in 2010 (MarsRex), by 2 industrial studies in 2012, and recently by another CDF study in mid 2014. The last study called MarsFast, foresees a rover of ~200 kg deployed from an NASA lander based on the Skycrane system.

- **Martian Moon (Phobos) Sample Return:** A more challenging mission in study is PHOOTPRINT, which aims at the return of surface samples from Phobos. The mission will make use of robotic elements to sample the surface in low-gravity. The mission has been initially assessed in 2 ESA CDF studies, an industrial study and more recently, under the assumption it could become a joint ESA-Roskosmos mission by a further CDF study. The mission would need the relevant technologies by approximately 2022.

- **JUICE (JUpiter ICy Moon Explorer):** An in-depth study of Jupiter and the Jovian icy satellites, with emphasis upon Ganymede, Europa and Callisto. The mission is due for launch in 2022, arriving at the Jovian system in 2030. The study of the Jovian system and its habitability will have profound implications for understanding extrasolar planets and planetary systems.

- **Future orbital missions:** There are quite a number of on-orbit applications requiring advanced robotics capabilities, which are envisaged to take place in the 2025-2035 timeframe. The UK is advised to position itself now to develop and demonstrate the capabilities required for these missions. The operators for these missions may range from space administrations to national governments to businesses. The following mission focuses are envisaged: rescue mission / orbit raising, planned orbit raising, inspection/support to deployment, deployment/assembly aid, repair, refuelling and orbit maintenance, mission evolution/adaptation, lifetime extension, and re/de-orbiting.

- **International Space Station (ISS):** The ISS continues to represent an excellent opportunity for scientific experiments to be conducted in space, amid the unique characteristics, constraints and pressures that environment brings.

5.2   KNOWLEDGE AND TECHNOLOGY TRANSFER

Exploration and Robotics is an area of the space industry that is driven heavily by technology and which faces huge challenges to achieve the mission science goals. It is mainly concerned with upstream activities with very little direct downstream benefits to the space industry. It does however have excellent potential for spin along activities allowing the spinning in of terrestrial technologies from other sectors as well as then spinning out the resulting technology advances.

Exploration and Robotics is an area of the space industry that is driven heavily by technology and which faces huge challenges to achieve the mission science goals. It is mainly concerned with upstream activities with very little direct downstream benefits to the space industry. It does however have excellent potential for spin along activities allowing the spinning in of terrestrial technologies from other sectors as well as then spinning out the resulting technology advances.

The European Commission funded Space Robotics Strategic Research Cluster (SRC) is undertaking a thorough analysis of the KT & TT potential for space RAS technologies. Early findings have revealed that current advances being made in R&D projects on space RAS could have significant knock-on effects in the many sectors including

- Nuclear decommissioning: for post operational clear-out, initial decommissioning, interim decommissioning and final demolition).

- Health & care: for robotic surgery, diagnostics, independent living, nursing systems, prosthetics, and analysis and therapy).

- Emergency services: for improved responsiveness, reduced risk to life, and more efficient deployment).

- Deep mining: for exploration, excavation, refinement, in wind energy for turbine inspection & maintenance.

- Water industry: for asset inspection, maintenance and health condition monitoring.

- Agriculture industry: for crop inspection and precision farming.

The markets associated with each of these sectors are expected to undergo huge growth in the coming years, and the adoption and insertion of RAS-based products and services into these applications is expected to deliver economic benefits of at least $1.9 trillion by 2025.

The UK has a great deal of expertise and assets in each of these areas to enable the development and testing of space RAS in other scenarios. Assembling major stakeholders and thought leaders from these sectors across the UK would represent an excellent way forwards to facilitate the knowledge transfer of the state of the art in these fields. Over the past 5 years, the space sector has been a member of the Autonomous and Intelligent Systems Partnership (AISP) made up of industry and academia co-funded by UK Engineering and Physical Sciences Research Council (EPSRC). The members of the partnership have repeatedly noticed commonality between the needs of the various sectors and this cross-pollination is proving to be beneficial to all parties involved.

FIGURE 9:

Planetary rover platform technology for agriculture applications [Courtesy RAL Space]

5.3   PUBLIC & EDUCATIONAL OUTREACH

Space RAS is a fantastic topic to engage with the public and help stimulate young people's interest in the STEM subjects. The recent Rosetta landing on a comet, an ESA mission, has demonstrated how robotic missions can be inspirational to people and our society. The more recent Principia mission involving British astronaut Tim Peake upon the ISS has also made significant public outreach thanks to the efforts of the UK Space Agency, which has allowed hundreds of schools across the UK have had the opportunity to engage with space and some of the science and technology involved, and how it impacts upon the rest of our lives.

One high-profile experiment conducted by Major Peake was part of ESA's METERON (Multi-purpose End-To-End Robotics Operations Network), which aims at developing the communications networks, robot interfaces and the controller hardware required to control robots from large distances, such as planetary orbit. This knowledge will be used to inform future exploration missions, such as controlling Mars rovers from Martian orbit or similar scenarios on the Moon. The experiment involves Major Peake tele-operating the "Bridget" Rover, stationed at the Airbus D&S Mars Yard in Stevenage, Hertfordshire, from the ISS. This tested the "delay-tolerant network", a precursor to a wider "Space Internet".

The experiment has brought the topic of complex tele-robotics to the public eyes through major news networks in the UK and beyond. Many programs for schools and schoolchildren coincided with various elements of the Principia mission to help youngsters to develop key skills for the future. For examples, the program Destination: Space has used live events and showcases across the UK to feature space manipulators and end-effectors to enable the children gain hands-on experience of operating a robot; the Earth to Mars Theme Day @ Bristol has used the rover concept to get children into computer programming and coding.

FIGURE 10:

Tele-operating a rover in a simulated cave at Airbus Mars yard from the ISS [Courtesy Airbus DS Ltd]
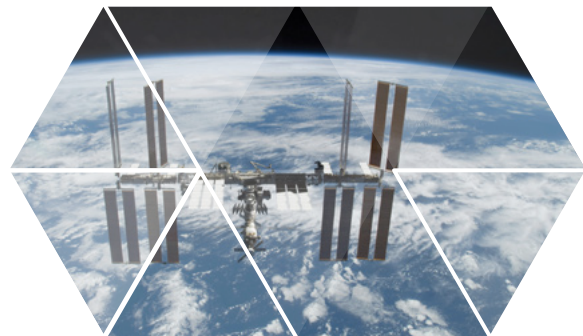
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[3] Yang Gao, (Ed.) Contemporary Planetary Robotics – An Approach to Autonomous Systems, pp. 1-450, Wiley-VCH, ISBN-13: 978-3527413256, August 2016.

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So far space missions have been either robotic or human. In the future we will see robotic and autonomous systems used far more to support humans explore, live and work in deep space. RAS is essential to deliver these exciting challenging space exploration missions. Overcoming these challenges advances technology that can be used back here on Earth to the benefit of society and economy.

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Sue Horne, Head of Space Exploration
UK Space Agency