UK-RAS White papers

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UK-RAS NETWORK
ROBOTICS & AUTONOMOUS SYSTEMS

Interoperable Robotics Proving Grounds: **Investing in Future-Ready Testing Infrastructures**

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FOREWORD

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 funded bodies and charities, the Network provides academic leadership and expands collaboration with industry while integrating and coordinating activities across the UK.

This white paper explores the need for interoperable robotics. As we move towards a society that is supported and enhanced by robotic and autonomous systems (RAS), we will increasingly require multiple robots of different configurations or from different manufacturers to operate in the same location. If multiple robots are not able to operate in the same space, then at best we will need to limit the types and numbers of robots, but at worst they will interfere with each other and cause accidents. Fortunately, the problem of interoperability can be tackled, but only if we act now; the longer we neglect this important topic, the more challenging it will be to change or 'retro-fit' robots operating in the real world. I hope this excellent white paper will enable research and development to ensure the UK can benefit from increased deployment of robots in all sectors towards a safe, secure and ethical future.

The UK-RAS white papers 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 updates for these white papers so your feedback is essential - whether it be pointing out inadvertent omissions 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:
info@ukras.org.uk
We look forward to hearing from you!

Prof. Robert Richardson
Chair, UK-RAS Network

Sina Sareh,
(Royal College of Art)

Oriol Badia,
(Malloy Aeronautics)

Robert Skilton,
(RACE, UKAEA)

Mirko Kovac,
(Imperial College London)

Sabine Hauert,
(University of Bristol)

Alexander Phillips,
(National Oceanography Centre)

Edward Cole,
(Katlas Technology)

Robert Richardson,
(University of Leeds)

Giuseppe Napo Montano,
(Arrival)

Other Contributors:
We would like to thank all the other contributors in shaping this white paper. Aaron Prather (ASTM International), Mark Emerton (Frazer Nash Consultancy), Jonathan Walker (Innovate UK KTN), Saina Akhoond (Foster and Partners), Albert Demargne (Royal College of Art), Mohammad Soorati (University of Southampton), Shahrooz Shahin (Royal College of Art), Rasoul Sadeghian (Royal College of Art), Ayodeji Abioye (University of Southampton), Ipek Caliskanelli (RACE), Perikilis Charchalakis (Vetronics Research Centre), Masoud Fakhimi (University of Surrey), Sharmin Fattahi (Royal College of Art), Charlotte Glaysher-Jones (Satellite Applications Catapult), Liam Braeger (Satellite Applications Catapult), Matthew Goodlife (RACE), Aron Kisdi (Oxford Dynamics), Marcos Mayorga (Katlas Technology), Josef Musil (Foster and Partners), Jesse Opoku (Wootzano), Tomoki Sakue (Tokyo Electric Power Company), Aren Sena (Foster and Partners), Bahbak Hashemi-Nezhad (Royal College of Art).

EXECUTIVE SUMMARY

The increasing adoption of robots in industrial applications demands seamless communication and collaboration among a diverse range of robotic systems, a phenomenon known as interoperability. The urgency for interoperability arises from the ever-expanding use cases and innovations in robotic systems from various vendors, necessitating secure, scalable, and shareable multi-vendor interaction. However, several challenges hinder the effective implementation of interoperability, such as rapid technological changes, lack of standardisation, proprietary technologies, different levels of system autonomy, safety and security concerns, incompatibility with legacy systems, and a shortage of skilled professionals in the area.

This white paper delves into the nuances of interoperability in robotics proving grounds (also known as test beds) and offers insights into the capabilities and limitations of the current landscape. It advocates for the development of standardised testing environments, along with rigorous experimental methods and metrics. These tools are crucial for shaping regulations, attaining certifications, and effectively managing the capabilities of interoperable assets throughout their lifecycle. Assessing government initiatives' efficacy and suppliers' compliance with interoperability standards is paramount.

The United Kingdom is strategically positioned to be a significant player in robotics interoperability, courtesy of its strong foothold in the energy and transport industries, such as offshore and aerospace, and an impressive network of research intensive universities and collaborative platforms. These institutions are engaged in pioneering research in areas such as modelling bio-inspired swarm systems, multi-robot coordination, sensor fusion, advanced communication, cybersecurity, and artificial intelligence.

To capitalise on the UK's capabilities in robotics, the white paper recommends a multi-pronged approach. It advocates for the government to nominate experts from various sectors to participate in both national and international standardisation activities, and to establish national committees focused on robotics interoperability standards. Encouraging partnerships among government, academia, and industry is also crucial, with a focus on pre-competitive collaboration to accelerate industry growth.

It is recommended to establish proving grounds and research centres for practical experimentation and development in robotics interoperability.

Furthermore, the UK should actively adopt and implement international standards for robotics interoperability, particularly in government-run programmes to set a benchmark for the private sector. Alignment of national regulations with international standards is essential, along with continual updates to facilitate standard adoption. The white paper also suggests supporting pilot projects that emphasise standardisation in robotics interoperability and highlights the importance of demonstrating the benefits through case studies. Organising competitions and challenges that incentivise the development of interoperable robotic solutions based on standard protocols is encouraged. Lastly, financial backing for standardisation efforts, including sponsoring participation in standardisation committees and funding research into standards development, is deemed essential.

"Robotics interoperability refers to the ability of diverse robotic systems to communicate and collaborate effectively through standardised interfaces and protocols. With the projected growth of the industrial robotics market from USD 48 billion in 2022 to USD 142 billion in 2032, the importance of achieving interoperability becomes evident. A cohesive and interoperable ecosystem allows robots from different vendors to work together seamlessly, unlocking the full potential of robotics technology and enabling its widespread adoption across various industries."

CONTENTS

1. THE ROBOTICS INTEROPERABILITY CHALLENGE

As the demand for specialised robots grows, it becomes increasingly vital for a wide range of systems to communicate effectively. This not only necessitates the exchange of information between various robotic systems but also the capability to interpret, understand, and utilise that information meaningfully [1]. However, this seamless communication and collaboration between specialised robotic systems, known as robotics interoperability, see examples in FIGURE 1 and FIGURE 2, is currently constrained by a number of key factors. These include, but are not limited to, the lack of standardisation, the prevalence of proprietary technologies, diverse levels of system autonomy, safety and security issues, and incompatibility with legacy systems [2, 3].

The integration of systems with varying levels of autonomy, from manual control to fully autonomous, requires a smooth transition to avoid conflict. Safety protocols need to be established to ensure secure command exchanges and mitigate risks like collisions. For robots to exchange meaningful data, standardised ontologies are required enabling robots to understand the data they receive in the context that it was sent. Retrofitting legacy systems for interoperability is often complex and costly, thus future designs should account for it. In addition, addressing these challenges requires the development of methods to measure interoperability performance, which will ensure efficient collaboration among different robotic systems, ultimately maximising their potential.

FIGURE 1:
Depiction of interoperability among heterogeneous teams of robots operating across the water surface for a shared goal, e.g. environmental monitoring. Images are courtesy of the National Oceanography Centre and Malloy Aeronautics Ltd.

The impact of robotics interoperability problems on the industry is multifaceted. Firstly, it hampers efficiency and productivity, as companies often find it difficult to integrate new robotic systems with existing infrastructure due to compatibility issues. This leads to increased costs in terms of both time and resources. Secondly, the lack of interoperability stymies innovation, as developers and manufacturers are often confined to proprietary technologies and unable to leverage advancements made by others. Lastly, it affects scalability. Businesses looking to expand or diversify their robotic operations face roadblocks due to interoperability issues, which can deter investment and slow down technological progress within the industry.

> "Interoperable robotics proving grounds are the crucibles where innovation unites, forging the future of collaborative robotics."

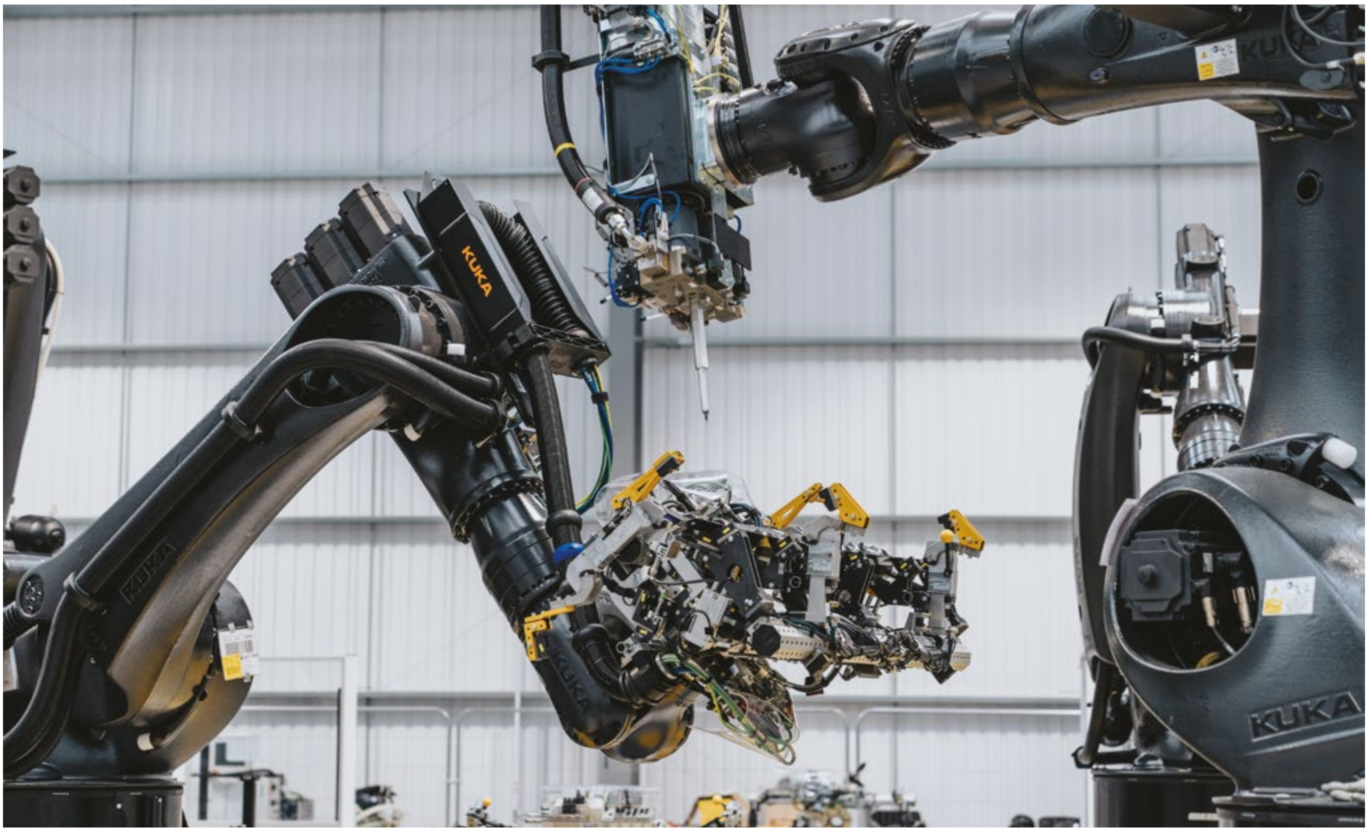


FIGURE 2:
Robots collaboratively working in unison to achieve a common mission objective: Electric vehicle's cabin assembled using advanced co-operative robotic platforms at Arrival's microfactories in Bicester, Oxford.

2. GLOBAL VISION AND COORDINATION TOWARDS INTEROPERABLE ROBOTICS PROVING GROUNDS

The global vision on interoperability among multi-vendor teams of robots in robotics proving grounds (physical or virtual test beds) is to create standardised and interconnected environments as well as testing procedures and metrics to evaluate the co-operation performance of robots and components in a consistent and objective manner [4]. It aims at promoting collaboration and information exchange among different stakeholders to advance co-deployment of robotics technologies. This includes promoting the development of common interfaces and protocols for robotics systems, which enable different systems to communicate and work together seamlessly and efficiently to achieve common goals.

This vision has gained traction in recent years due to the increasing adoption of robotics in various industries and applications. Key technical requirements of such testing environments encompass scalable infrastructure and flexible configurations capable of accommodating the evolving needs of the rapidly advancing robotics field. Emphasising real-world relevance, they should replicate complex scenarios with high fidelity, incorporating realistic sensors and actuators, with the same or very similar specifications and capabilities as the ones used in real-world systems, to ensure authentic evaluations. To uphold reliability and consistency, standardised protocols and metrics should be established, enabling reliable comparisons and benchmarking. Moreover, privacy and security considerations should be paramount, with robust data protection measures, encryption protocols, and ethical guidelines in place. See TABLE 1 summarising the relevant requirements, here we name them as VESICS.

VESICS
Key Requirements for Interoperable Robotics Proving Grounds

V	S	C
VERSATILITY Scalable and flexible test beds host diverse robotic systems, adapt to various scenarios, and allow for iterative development and evolution of the systems in use.	**SECURITY** Safeguard data, systems, and intellectual property of participating vendors by encryption, access control, and secure communication channels.	**CONSISTENCY** Consistent testing conditions ensure repeatability and reliability in results, required for drawing valid conclusions about robots' interoperability.
E	**I**	**S**
EVALUATION Comprehensive metrics assess robots' communication, coordination, and task execution, including data exchange and response times.	**INTERACTION** Featuring user-centred interfaces, test beds facilitate easy configuration, control, varying test scenarios, and monitoring of the testing process.	**SIMULATION** Realistic virtual environments closely replicating real-world situations are crucial for assessing robots' collaborative effectiveness.

TABLE 1:
Key requirements for interoperable robotics proving grounds

> Advancing interoperability in robotics necessitates the creation of standardised, interconnected environments with rigorous testing procedures, fostering collaboration among stakeholders, and ensuring scalability, real-world relevance, and utmost security.

Several international organisations work to develop and refine standards for robotic systems interoperability, respective test beds, and certification processes. Some key organisations and initiatives, categorised by the location of their headquarters include:

Belgium:
In Europe, the primary entity overseeing electrical engineering's technical standards is the European Committee for Electrotechnical Standardization, known as CENELEC. With a central focus on electrical engineering norms, CENELEC also delves into mechanical and industrial standards that often pertain to industrial robotics [5].

Switzerland:
ISO (International Organization for Standardization) develops standards through collaboration with representatives from its member countries. ISO/TC 299 is the technical committee responsible for developing standards for robotics, including those that promote interoperability among robotic systems [6]. ISO 3691-4 covers safety aspects of autonomous mobile robots (AMRs) in industrial environments including interoperability with other robotics assets and human operators [7]. NEST is a modular research and innovation building of Swiss Federal Laboratories for Materials Science and Technology (EMPA) and Swiss Federal Institute of Aquatic Science and Technology (Eawag). At NEST, new technologies, materials and systems are tested, researched, further developed and validated under real conditions, see FIGURE 3 and FIGURE 4 for examples of robotics proving grounds within the Drone Hub of the NEST [8].

Germany:
The VDA 5050 Standard, formulated by the VDA (German Association of the Automotive Industry), focuses on ensuring interoperability and communication among autonomous transport systems including automated guided vehicles (AGVs). The standard is vital for enabling different manufacturers' systems to communicate and work efficiently together, particularly in logistics and material handling within the automotive industry and beyond [9].

United States of America:
ASTM Committee F45 on Robotics, Automation, and Autonomous Systems develops standards for industrial/commercial robotics, and autonomous systems including relevant terminologies, practices, classifications, guides, test methods, and specifications. The Committee has its standards published in the Annual Book of ASTM Standards, Volume 15.08. F45's technical subcommittees are in charge of maintaining jurisdiction over these standards [10].

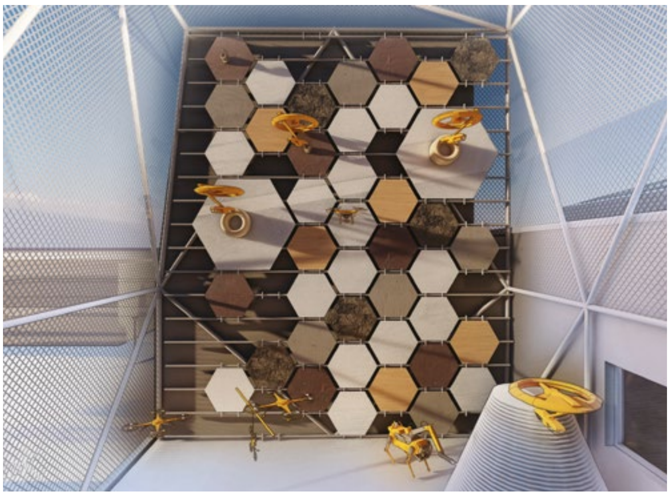


FIGURE 3:
Nest's Drone Hub test bed: aerial additive manufacturing façade

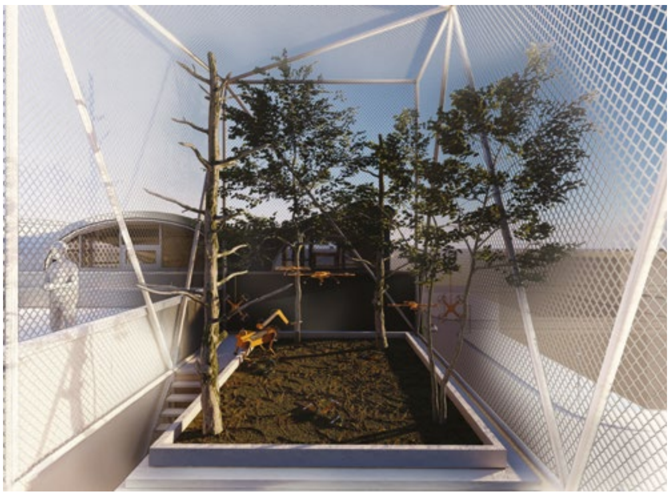


FIGURE 4:
Nest's Drone Hub test bed: biosphere for environmental sensing

IEEE (Institute of Electrical and Electronics Engineers) committees work on standardising communication protocols, interfaces, and best practices for robotic systems to promote interoperability. Prominent examples include ISO/ IEEE 21451: Smart Transducer Interface for Sensors and Actuators [11], IEEE P1872.1: Ontologies for Robotics and Automation [11], IEEE P2020: Automotive System Image Quality Assessment Framework, relevant in scenarios where autonomous vehicles, which are a form of robotics, need to communicate image data with other systems [13], and ISO/ IEEE 11073: Interoperability between various health and medical devices [14].

NIST (National Institute of Standards and Technology) is a U.S. government agency that develops and promotes measurement, standards, and technology. NIST has initiatives and research programmes focused on robotics, such as the Robotics Test Facility, which aims to advance robotics technology by facilitating the development of interoperability standards and test methods [15].

The OPC Foundation is an industry consortium that creates and maintains standards for open connectivity of industrial automation devices and systems. OPC Unified Architecture (OPC UA) is a platform independent machine-to-machine communication architecture for industrial automation enabling seamless data exchange and interoperability among various devices, including robotic systems, in manufacturing and other industries [16].

The Object Management Group (OMG) is an international consortium that develops and maintains computer industry standards, including the Data Distribution Service (DDS) for real-time systems used by the Robotic Operating System 2 (ROS 2). These standards facilitate communication and data exchange among robotic systems from different vendors [17].

The UMass Lowell NERVE Center in the United States is an interdisciplinary robotics testing, research, and training facility that evaluates robotic capabilities, human performance, as well as human-robot interaction and develops relevant test methods and metrics [18].

MassRobotics Interoperability Standard is a set of guidelines which will allow different brands of mobile robots to work together in the same environment, similar to the VDA 5050 standard from Germany [19].

DARPA (Defense Advanced Research Projects Agency), a U.S. Department of Defense agency that supports the development of advanced technologies, has funded various projects and initiatives aimed at advancing robotic interoperability, such as the Robotics Collaborative Technology Alliance (RCTA) [20].

RoboCup: RoboCup is an international research initiative that focuses on the development of intelligent robots, with the goal of promoting artificial intelligence and robotics research. The RoboCup competitions serve as a proving ground for the interoperability of robotic systems developed by various research groups and institutions [21].

Japan:
The Japan Robot Association, also known as JARA, holds a prominent position as a technical body that substantially influences the nation's robotics standards and regulations. Though the government holds ultimate authority over these standards, JARA often plays a role in drafting them [22].

South Korea:
South Korea has adopted an unconventional stance on robotics standards. In 2020, a decision by South Korean authorities resulted in the removal of almost all robotics regulations to bolster the country's domestic robotics sector [23]. Consequently, robots in South Korea mainly need to align with ISO standards.

United Kingdom:
The British Standards Institution, commonly known as BSI, serves as the UK's national standards authority. BSI is instrumental in formulating technical standards encompassing a plethora of products and services, and additionally offers certification alongside services associated with standards to enterprises. A notable standard is BS 8611, which pertains to robots and robotic devices [24]. This standard furnishes insights on pinpointing conceivable ethical risks and lays down guidelines for the design and functioning of robots throughout their entire lifecycle. It supplements pre-existing safety stipulations catered to diverse robot categories, such as industrial, personal care, service, and medical robots. In the UK, several organisations work on the development of interoperable proving grounds for robotic systems. These organisations often collaborate with industry partners, research institutions, and government agencies to develop and refine interoperability standards, test beds, and certification processes. Some key UK organisations include but are not limited to RACE (Remote Applications in Challenging Environments); a robotics and autonomous systems test facility based at the UK Atomic Energy Authority's Culham Science Centre. It operates a proving ground for robotics and autonomous systems in challenging environments, including interoperability testing [25].

The Catapult Centres, technology and innovation centres established by Innovate UK to promote the development of emerging technologies in various sectors operate research facilities, testing environments, and expertise to support the development of multi-platform robotic systems [26].

The Digital, Autonomous and Robotics Engineering (DARE) Centre at the Offshore Renewable Energy (ORE) Catapult's testing facility in Blyth hosts a robotics assembly bay, an airborne robotics test zone, three dry docks with 20,000 m3 capacity and test control rooms linked to the docks via a live environment monitoring system. These test beds foster collaboration between academia, industry, and government, promoting knowledge sharing, innovation, and the development of best practices to drive the UK's leadership in robotics and automation. UK universities have developed various construction, testing and proving grounds including, to name a few, the ambient assisted living studio, flying arena, and a 16,000 Ltr test pool at Bristol Robotics Laboratory [27], orbital and surface robotics test beds at the University of Surrey [28], Imperial College London's Multi Terrain Aerial Robotics Arena enabling engineers to create extreme conditions such as fire, smoke and heat to simulate how the next generation of drones will perform in challenging environments [29].

The EPSRC National Facility for Innovative Robotic Systems at the University of Leeds is a national resource for the testing, including a high frequency communications and sensing test bed, as well as fabrication of complex systems which uses a small research facility (SRF) model that allows academics and industrialists easy access to the facilities [30].

Royal College of Art's new campus in Battersea features an integrated air-land-water robot mobility arena where diverse types of robotic systems can be tested within a single trackable space [31], see FIGURE 5. In addition, recently a number of UK cities have been hosting trials of robot fleets, for example in July 2023 the DPD has announced plans to expand its robot delivery services to 10 UK towns and cities in the next 12 months [32].

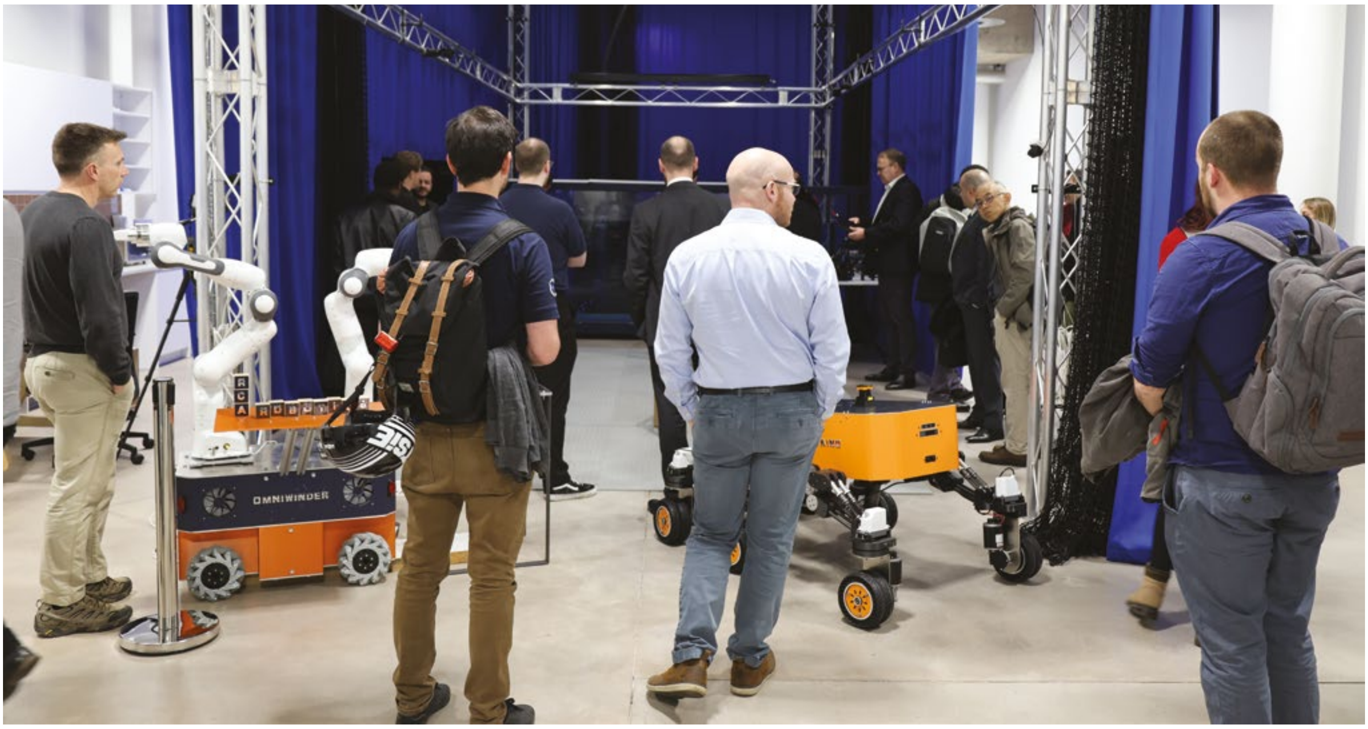


FIGURE 5:

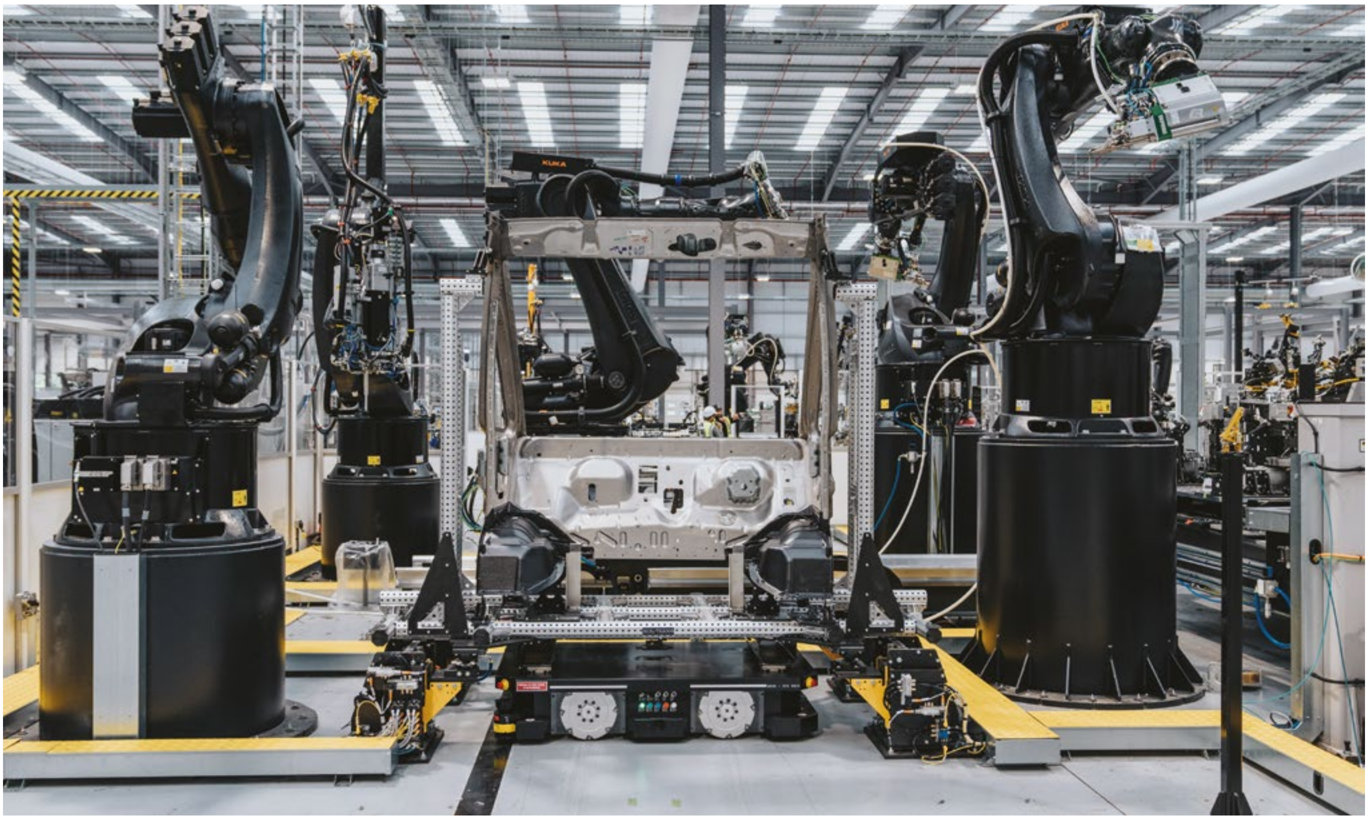
Integrated air-land-water robot mobility testing environment at Royal College of Art's Robotics Laboratory in Battersea, London, UK

3. UK OPPORTUNITIES AND STRENGTH

In the UK, the development of interoperable robotics and autonomous systems proving grounds is characterised by notable strengths, promising opportunities, inherent weaknesses, and potential threats, see TABLE 2 for the relevant SWOT analysis.

Strengths include the UK's position as a world leader in offshore, aerospace and automotive industries, which acts as a solid foundation for robotics applications in these sectors. Coupled with the nation's renowned universities and research institutions, where a focus on real-world applications, human safety, and security is emphasised, ensures the development of practical and impactful solutions. Additionally, the UK boasts established collaborative networks and innovation hubs such as UK-RAS (Robotics and Autonomous Systems) Network and Catapult centres, which foster collaboration and streamline innovation. The growing UK RAS market in various areas such as healthcare, agriculture, and manufacturing indicates a conducive environment for continued growth in robotics.

Opportunities are presented through shared interoperable resources, which foster an economy of scale, reducing costs and promoting collaborative efforts. This sharing model is especially beneficial for Small and Medium Enterprises (SMEs) by providing them access to interoperable testing beds to fast-track market creation and innovation. Additionally, the proving grounds can serve as centres for cross-industry collaborations, international partnerships, and addressing societal challenges through robotics.



Arrival's microfactory in Bicester, Oxford, where multiple industrial robot arms and mobile robotic platform co-assemble electric vehicles.

Weaknesses encompass the relatively fragmented nature of R&D in the UK, with limited in-house abilities for mass production of standardised systems, which may slow down the pace of innovation. The potential complexity and challenges in integrating different systems due to varying standards and regulatory limits can also impede the efficiency of interoperable proving grounds.

Threats include concerns regarding data security and intellectual property protection. The open nature of interoperable test beds with multiple entries to the system might expose sensitive information to competitors.

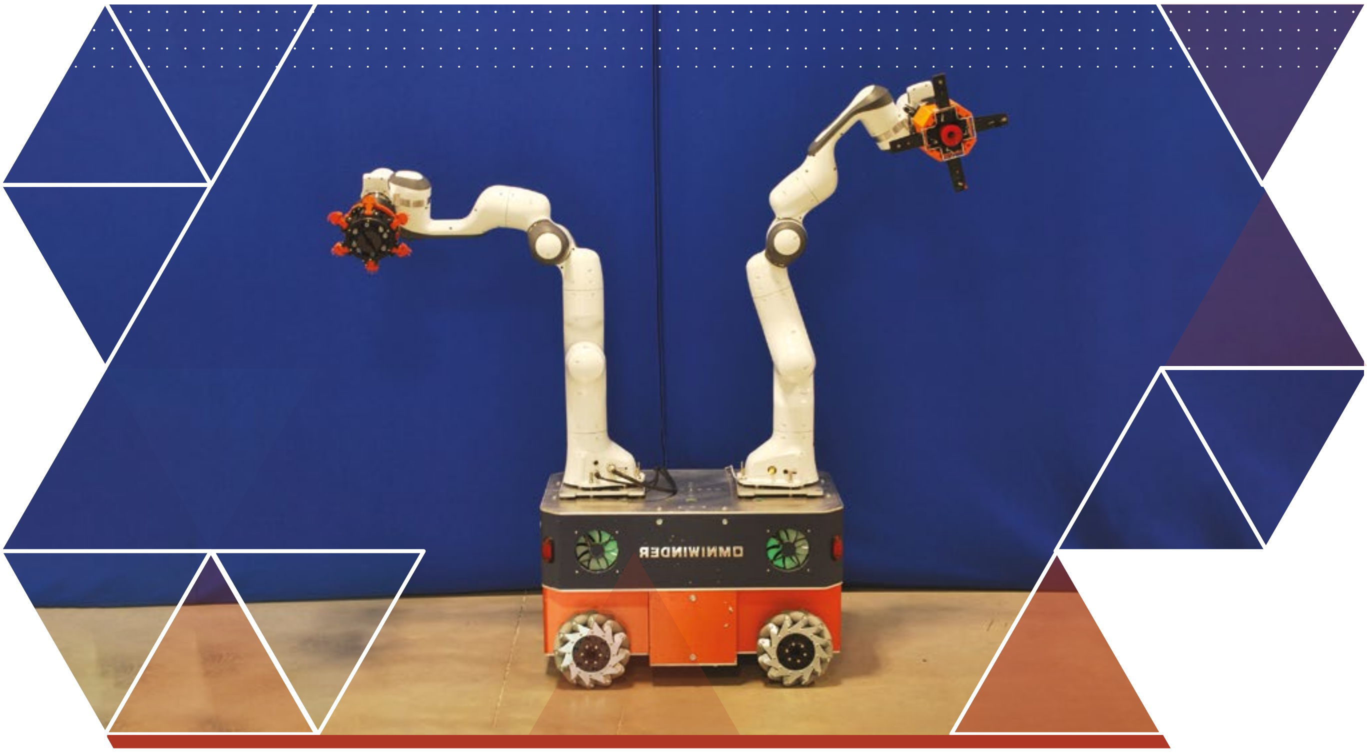
There's also stiff competition from other countries with advanced proving grounds, which could overshadow the UK's efforts. Additionally, differing goals among stakeholders could lead to conflicts, hampering effective collaboration.

Overall, the United Kingdom has a well-established ecosystem for robotics research, development, and innovation, providing numerous opportunities and strengths for advancing robotics interoperability. By leveraging these strengths, the UK can position itself as a global leader in the development and deployment of interoperable robotic systems.

TABLE 2:
SWOT analysis

Malloy Aeronautics, a leading aerospace company headquartered near London, UK, offers a diverse portfolio of cutting-edge aerial robotic platforms.

4. RESEARCH PROGRAMMES AND PROJECTS ACROSS THE UK



The UK has been a vibrant hub for a plethora of research programs and projects, showcasing an acute emphasis on robotics with applications as broad as offshore infrastructure maintenance to nuclear decommissioning, and autonomous manufacturing, where, in many of them, multi-platform interoperability is a key requirement. These programmes demonstrate the UK's commitment to advancing robotics and promoting interoperability:

- **FAIR-SPACE Hub:** Funded by EPSRC, the FAIR-SPACE (Future AI and Robotics for Space) Hub is a collaborative research hub, led by the University of Surrey, involving several UK universities and research institutions. It aims to advance the state of the art space robotics and autonomous systems, including the development of robotic systems for tasks in the context of satellite repair, telescope assembly, and planetary exploration [33].
- **ORCA Hub (Offshore Robotics for Certification of Assets):** The ORCA Hub is another EPSRC-funded hub led by the Edinburgh Centre for Robotics that focuses on developing robotics and AI technologies for the offshore energy industry. The hub hosts research on various robotic systems including aerial drones and underwater vehicles to enable inspection, and asset certification in offshore environments [34].
- **Rain Hub (Robotics and AI in Nuclear):** Funded by EPSRC and led by the University of Manchester, the Rain Hub aims to develop advanced robotics and AI technologies for deployment in the nuclear industry with projects focusing on challenges such as remote handling, decommissioning, and waste management [35].
- **NCNR (National Centre for Nuclear Robotics):** Led by the University of Birmingham, the NCNR is a collaborative centre supported by EPSRC that focuses on research and development of robotics and AI technologies to make radioactive environments safe [36].

- **Robotics and AI in Extreme Environments:** Innovate UK funded several projects under the "Robotics for a Safer World" program. This program aimed to develop robotic systems and AI technologies for deployment in extreme environments, such as deep-sea, space, and nuclear facilities, where interoperability among robotic systems is important [37].
- **CASCADE (Complex Autonomous aircraft Systems Configuration, Analysis and Design Exploratory)** is a large UK research project on unmanned aircraft, involving the University of Southampton and four other leading universities. The project aims at advancing aerial robotics technology through research in six key areas (Safety, Autonomy, Capability, Scalability, Agility, and Integration) and practical case studies. The project aims to shape the technological and regulatory standards that can contribute to a safe, commercially and scientifically vibrant industry [38].

Example UK Projects dealing with interoperability challenges include:

- **Offshore:** Multi-platform Inspection, Maintenance and Repair in Extreme Environments (MIMRee) employed a heterogeneous team of robots including an autonomous boat, an UAV and a crawling robot integrated with an autonomous wind turbine blade repair system to demonstrate remote wind turbine blade repair, see FIGURE 6 [39].
- **Underground:** Pipebots deploys swarms of miniaturised robots in buried pipes together with other emerging in-pipe sensor, navigation and communication solutions with long-term autonomy to enable failure free operation preventing unnecessary and unplanned road excavation, see FIGURE 7 [40].
- **Construction:** Aerial Additive Building Manufacturing (Aerial-ABM) used a swarm of flying drones integrated with specialised equipment for the deposition of construction materials to enable 3D printing of buildings and building components, see FIGURE 8 [41].

FIGURE 6:
Multi-platform Inspection, Maintenance and Repair in Extreme Environments (MIMRee)

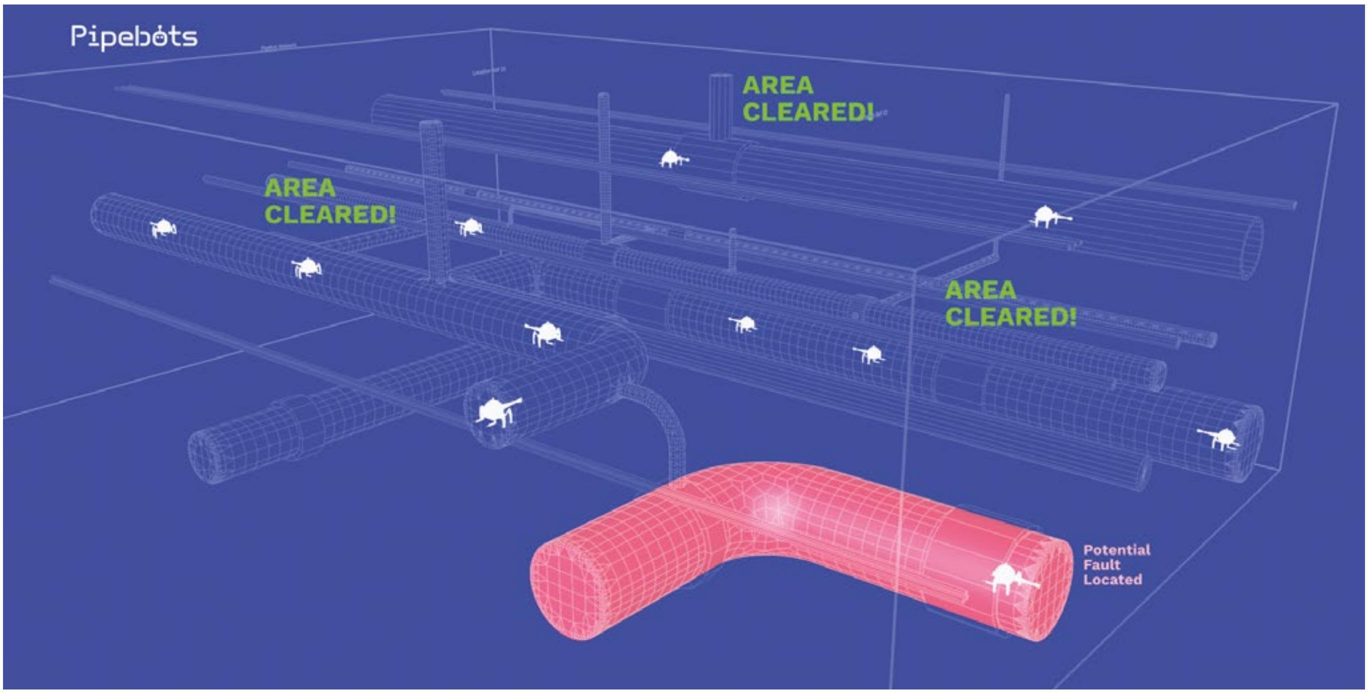


FIGURE 7:
Pipebots

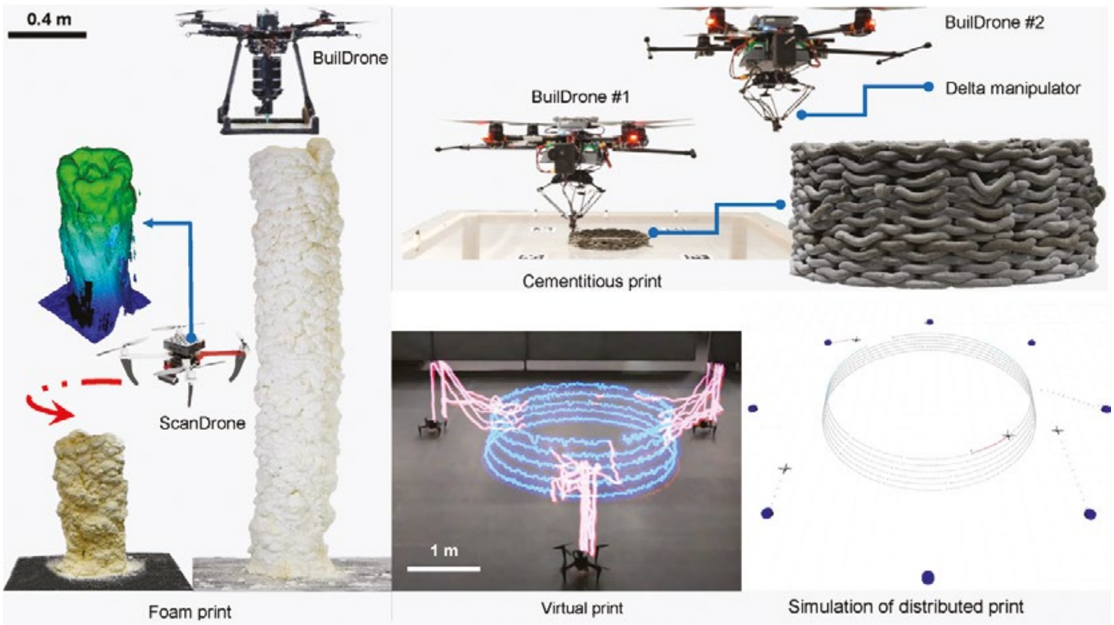


FIGURE 8:
Aerial Additive Building Manufacturing (Aerial ABM)

5. STAKEHOLDER ENGAGEMENT: KEY TO ACHIEVING INTEROPERABILITY

Interoperability problems are pervasive across all areas of industrial operations ranging from underwater construction to aerial surveying, automotive manufacturing, testing facilities, and power generation.

The array of stakeholders typically encompasses entities such as robot manufacturers, control system purveyors, government regulatory bodies, environmental advocacy groups, insurance companies, and local communities. However, the imperative to collaborate with sector-specific classification and certification organisations cannot be overstated. Engaging with prominent organisations such as DNV (Det Norske Veritas) in Norway, MCA (Marine and Coastguard Agency) in the UK, HSE (Health and Safety Executive) in the UK, CAA (Civil Aviation Authority) in the UK, VCA (Vehicle Certification Agency) in the UK, and the IAEA (International Atomic Energy Agency), is instrumental in assuring compliance with relevant legal frameworks and safety standards.

In the context of aerial robots, compliance with the Air Navigation Order (ANO) is obligatory [42], and it is advisable to ascertain if a Certificate of Airworthiness (C of A) is needed for specific operations. In marine environments, adherence to the UN Convention on the Law of the Sea, 1982 (UNCLOS) which establishes a legal framework for marine and maritime activities [43] and the International Convention for the Prevention of Pollution from Ships (MARPOL) is of great importance. A guidance by the RIMA project at University of York for identifying applicable rules and regulations for unmanned marine robots for inspection and maintenance can be found in [44]. Furthermore, in the realm of nuclear robotics, adherence to regulations laid down by The Office for Nuclear Regulation (ONR) in the United Kingdom is mandatory. Through these efforts, the robotics industry can foster a culture of safety and responsibility, ensuring that innovation thrives within a well-regulated and accountable framework.

The development of a robotics interoperability proving ground necessitates the establishment of an interconnected environment that promotes harmonious interaction and collaboration among a diverse array of robotic systems. Paramount considerations encompass the articulation of unambiguous objectives centred around interoperability within an specified context, the formulation of standardised communication protocols, and the emulation of real-world conditions characterised by multifaceted tasks necessitating cooperative efforts. The proving ground ought to exhibit modularity, adaptability, and a design imbued with safety and security considerations. Implementation of advanced monitoring and data collection systems is crucial for the analysis and enhancement of interoperability, while fostering synergistic relationships among researchers, engineers, and stakeholders is vital to drive perpetual refinement. Legal and regulatory concerns, encompassing data privacy and cybersecurity, must be meticulously addressed as well.

6. FROM INTEROPERABLE PROVING GROUNDS TO THE REAL WORLD

As robots become more capable and autonomous, there will be a greater need for collaboration among various robotic platforms to complete complex missions. The development of collaborative robotic systems will enable them to work together, leveraging their unique capabilities to achieve common goals more efficiently. Further incorporation of AI and machine learning algorithms in robotic systems will enable them to learn from their experiences in a more comprehensive way, and adapt to changing conditions. This would enhance the capabilities of robots in proving grounds, allowing them to perform more complex tasks and subsequently be capable of adapting to unforeseen situations in the real world.

> "Through the lens of robotics interoperability, we can envision a future where ubiquitous robots seamlessly integrate into our homes, workplaces, and daily lives, harmoniously enhancing our world."

7. RECOMMENDATIONS

To harness the UK's potential, the white paper proposes several strategic steps:

1. The UK government can nominate experts from academia, industry, and government bodies to participate in international and national standardisation activities and join relevant committees such as the ASTM International F45 Committee on robotics.
2. Establish national committees that focus on robotics interoperability standards. These committees can collaborate with international bodies and represent the UK's interests in the global standardisation process.
3. Encourage and facilitate partnerships between the government, academic institutions, and the private sector to work collectively on standardisation efforts. This could include setting up joint task forces or centres of excellence for robotics standards development. Pre-competitive collaboration is a vital catalyst for industry expansion.
4. Establish Proving Grounds (Test beds) and Research Centers where robotics interoperability can be studied and developed in practical settings. This can mimic successful approaches by the U.S. government in establishing test beds such as NIST (National Institute of Standards and Technology).
5. Actively adopt international standards for robotics interoperability within the UK and implement them across government-run programmes. This will set an example for the private sector to follow suit.
6. Ensure that national regulations are aligned with international standards, and update regulations to facilitate the adoption of standards for robotics interoperability.
7. Support and invest in pilot projects that employ standardisation in robotics interoperability. Showcase the benefits and feasibility of implementing standards through demonstrations and case studies.
8. Sponsor and organise competitions and challenges that incentivise the development of interoperable robotic solutions based on standard protocols.
9. Provide financial support for standardisation initiatives, including sponsoring participation in standardisation committees, and funding research into standards development.
10. Ethical and practical considerations should be taken into account including the importance of assuring that the standard holder is open and has no commercial agenda.
11. To future proof for unforeseen scenarios in artificial test beds, extensive coverage of application spaces is needed, and distance to reality should be minimised. In the real world, challenges may include meeting specific customers' requirements and the fact that testing may not be repeatable.

Workshop on "Interoperability in Robotics and Autonomous Systems Proving Grounds at the Royal College of Art on 16 February 2023

> The UK's leadership and long-term capabilities in developing interoperable applications within offshore, aerospace and automotive sectors, fused with the nation's renowned universities and research institutions, where a focus on real-world applications, human safety, and security is emphasised, ensures the development of practical and impactful solutions that can make the UK a global leader in the development and deployment of interoperable robotic systems.

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> “The future success of UK robotics industries won't come from just a few smart machines working alone, but from lots of machines working together perfectly, thanks to them being able to communicate and cooperate.”

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