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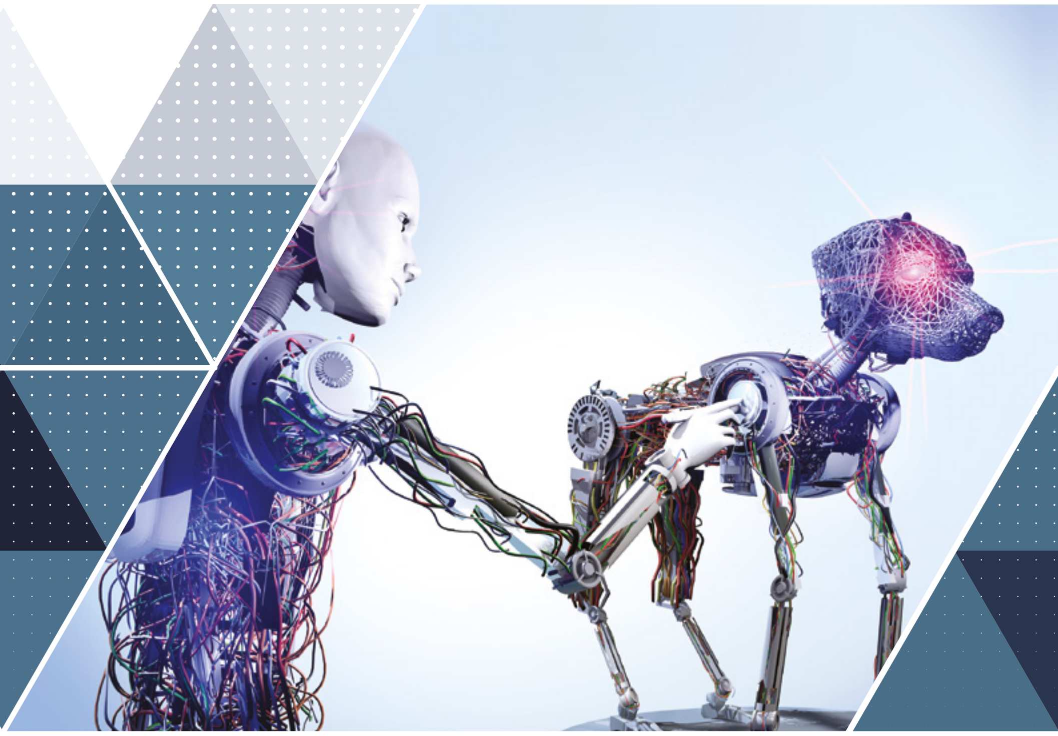
ROBOTICS & AUTONOMOUS SYSTEMS

Legged Robotics: **Agile and Dynamic Interaction**



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FOREWORD

LEGGED ROBOTICS: AGILE AND DYNAMIC INTERACTION

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 and expands collaboration with industry while integrating and coordinating activities across the UK.

This white paper explores the state of the art in legged robots. Until recently, legged robots were imaginations of science fiction or at best clumsy demonstrations in research labs. Research in the UK and overseas has developed legged robots to the point where they move smoothly and confidently over rugged real world terrain to undertake tasks. In the future, will legged robots be the primary form of robot? This is certainly an exciting possibility of the future. I hope the white paper will inspire future research, promote collaboration, and identify key areas of future growth in this fascinating area of RAS.

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 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 whitepaper@ukras.org.uk.
We look forward to hearing from you!

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EXECUTIVE SUMMARY

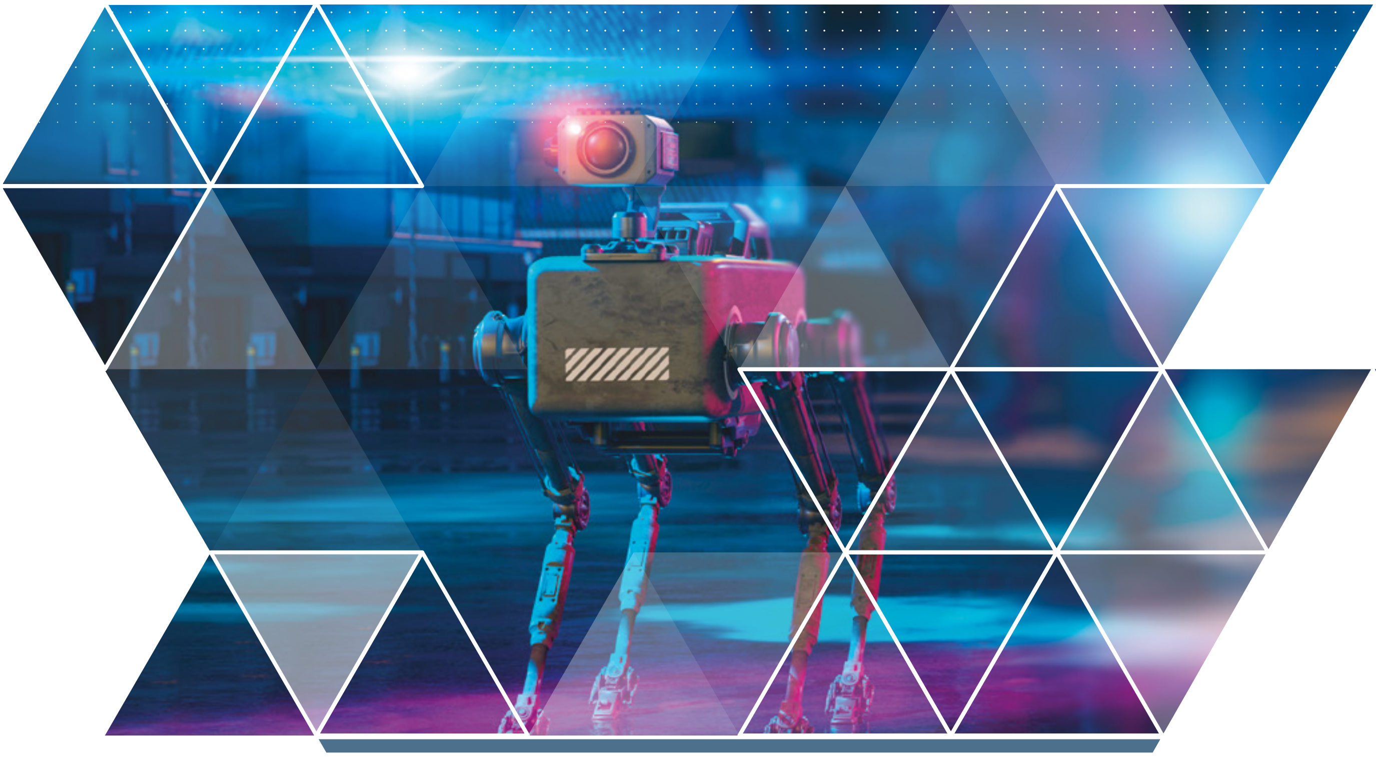
Legged robots have long captivated the general public. The robots in science fiction are often depicted as anthropomorphic bipeds either helping or threatening mankind. However, locomotion as a skill is deceptively complicated and underappreciated as we learn to walk as toddlers.. In reality the Homo Sapien is one of the few species to walk on two feet because of this challenge.

One of the main drivers for this research field is that our world is largely built with the human morphology in mind. Staircases, doorways, counter-tops and work stations are all built around the typical size of a human adult. Mobile robots in the homes and offices of our future need to adapt to our space, rather than the other way around.

The progress towards industrially feasible, technologically advanced walking robots is undeniable. While Boston Dynamic's Spot quadruped and Atlas biped have achieved a type of narrow super-human athleticism, other companies such as ANYbotics, Unitree Robotics and Ghost Robotics have brought products to the market which target different market segments; for example, industrial inspection, low-cost platforms and military applications.

The key development that has enabled rapid progress is force sensing and whole body balancing control. These core technological components have enabled compliant and flexible locomotion. Modern walking robots now adapt to the world's complexities rather than being brittle to the unexpected. Embedded computers in small form factor, industrial grade depth cameras, high quality MEMS IMUs and lightweight materials are other components which have contributed to the commercialisation of this generation of walking robots.

Within the UK, there is a vibrant research community working on legged robots. Several universities have invested in platforms and are carrying out research in a variety of sub-fields. Core problems such as high degrees of freedom compliant balancing and motion generation are popular in the more established groups while the demonstration of the platform and its application in field situations has drawn in researchers (for example in the energy and nuclear sector).



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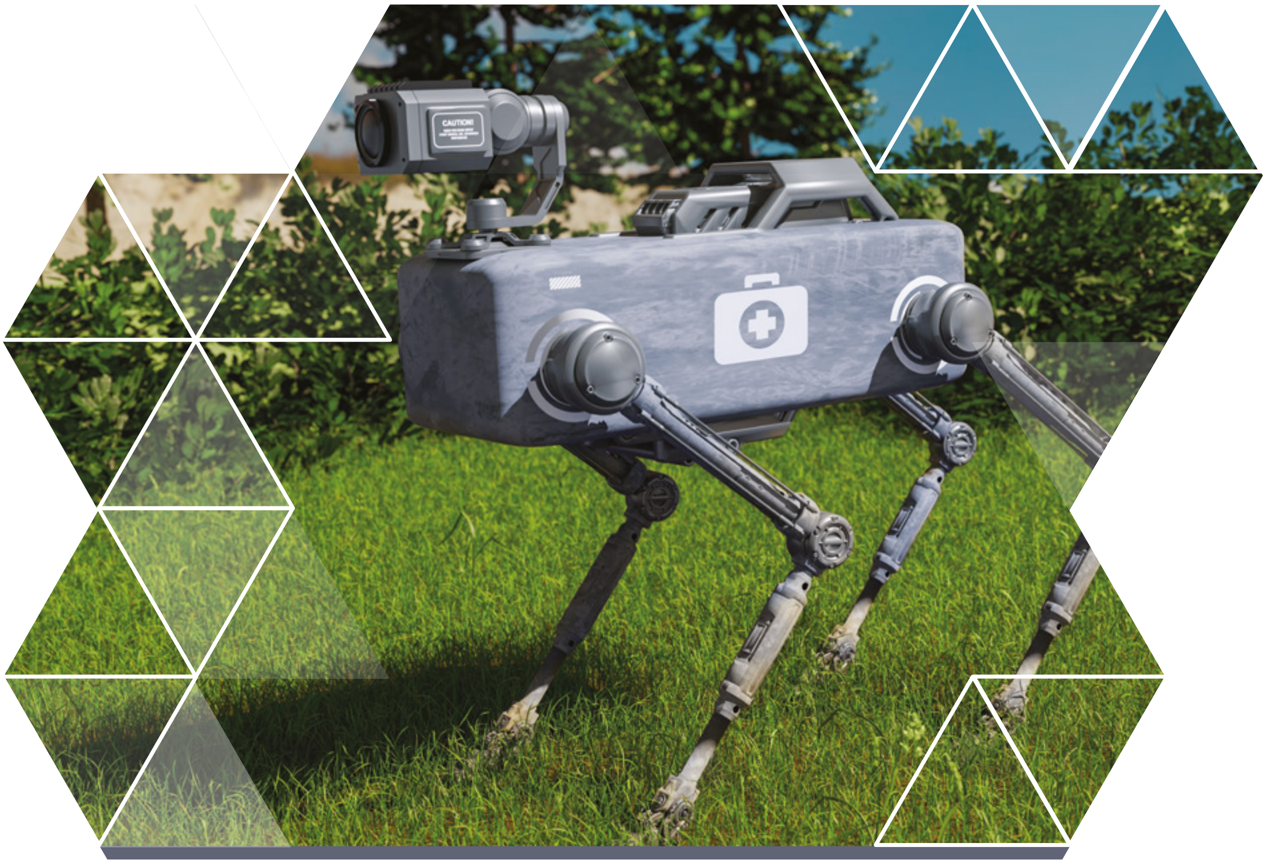

"The UK's efforts in legged robots have been a combination of fundamental scientific research (on the capabilities of motion planning, dynamic balance, state estimation and loco-manipulation) with demonstrations in industrial scenarios to showcase the emerging field."

1. TECHNOLOGY BRIEF

Mechanical walking systems actually date back to the 1960s. General Electric built a four-legged walking truck, powered by hydraulics, in the mid 1960s. It could carry an operator, push heavy railway sleepers and give tactile feedback to the operator, who needed to coordinate every motion of the legged truck. The goal was to develop an all-terrain mobility solution with military application. However, cognitive burden on the operator was high, the ride was rough and the platform was decommissioned shortly after.

Space exploration is another domain where legged robots have been promoted. A team led by Eric Krotkov and Reid Simmons in CMU developed the six-legged Ambler quadruped with funding from NASA which could cross soft and deformable terrains such as those found on the moon or nearby planets. Early approaches to sensor fusion and legged odometry were studied in their research papers. The hexapod design was promoted because of its ability to be statically stable at all times.

Meanwhile, an entirely different approach was being developed by Marc Raibert (first in CMU and then at MIT). A 3D one-leg hopper was created in 1983 and could actively balance with simple reflexive feedback control algorithms. It could hop in place, follow simple paths and maintain balance when disturbed. A core principle was the use of hydraulics to ensure a very quick reaction and to ensure power availability. Throughout the 1980s Raibert's group developed more complex biped and quadruped robots before commercialising the research as Boston Dynamics. Research continued with the famous BigDog series of gas-powered, all-terrain quadrupeds which were funded by a series of DARPA and US Defence grants. The LS3 (Legged Squad Support System) was the first robot that attempted to have a product capability - acting as a pack mule for the US Marines and able to carry 100s of pounds of supplies over hills, ravines and through forests. Since about 2015 Boston Dynamics shifted to electric actuation and created the refined product model of the much smaller Spot robot which has now been sold to hundreds of companies and research labs with applications including inspection, security, healthcare and entertainment.

Early humanoid robotics is much more associated with Japan. Honda started developing humanoid robots in the late 1980s and had various prototypes of self-regulating bipeds before the release of ASIMO in 2000. Challenges to be overcome were that of climbing and descending staircases, as well as perceiving obstacles before depth sensing technologies existed. Over 100 copies of ASIMO were created. Outside of Honda, the Japanese Ministry of Economy, Trade and Industry (METI) in collaboration with Kawada Industries developed the HRP series of robots (in the Humanoid Robotics Project). About 5 different generations of robots were developed. The HRP-2 robot is perhaps most recognisable. Japanese and also French funding projects have demonstrated the HRP-2 in mock industrial scenarios.

A key point of evolution of humanoid robotics was the DARPA Robotics Challenge. The DRC was not specifically focused on bipeds, but rather a biped was the most logical solution for manipulation of a series of tasks posed by a mock disaster response situation. Teams from across the world developed robots including several HPR-2 robots, self-built bipeds and multiple copies of the Atlas humanoid robot (developed by Boston Dynamics with DARPA funding) competed in a series of competitions over 3 years up to 2015. The winning team was the Hubo robot from KAIST (Korea) which demonstrated significant flexibility in achieving each of the eight tasks.

2. INTERNATIONAL PERSPECTIVE

It is notable that there are no UK-based manufacturers of the leading legged robots. Boston Dynamics (USA), ANYbotics (Switzerland), PAL Robotics (Spain), Unitree Robotics (China) being a few examples of growing companies in this sector across the world. Some research into mechanical design and development of legged robots is conducted, for example, in Imperial College and University of Bristol. However the degree of investment and knowledge build-up makes it difficult to compete against international players. UK research groups have tended to focus instead on collaboration and interaction with these organisations on the software level.

The University of Edinburgh is one of a few owners of a PAL TALOS humanoid, which they use to carry out research into dynamic coordinated motor control and human robot interaction within the MEMMO EU project. This is with the Laboratory for Analysis and Architecture of Systems (LAAS) in Toulouse, who also own an identical copy of the TALOS robot. Other international research with humanoids includes the research programme with the Cassie and Digit platforms developed by Agility Robotics which has produced about a dozen copies for research labs across the US and Canada. The Boston Dynamics Atlas robot is not available for public purchase at this time.

Oxford's Dynamic Robot Systems Group are part of the winning team of the DARPA Subterranean Challenge - an international competition to develop multi-robot collaborative exploration solutions for disaster response and exploration. Their team, called Cerberus, used multiple copies of the ANYmal from ANYbotics as well as both wheeled and aerial robots from University of Reno, Nevada and ETH Zurich. Within this competition, legged robots have proven to be surprisingly valuable. Wheeled robots immediately face limitations when terrain is rough or stairs need to be traversed. The top competitors in the challenge used combinations of the ANYmal robot, as well as several Boston Dynamics Spot in the finals of this competition that has been held in the United States in September 2021.

3. UK CHALLENGES AND STRENGTHS

The UK's efforts in legged robots have been a combination of fundamental scientific research (on the capabilities of motion planning, dynamic balance, state estimation and loco-manipulation) with demonstrations in industrial scenarios to showcase the emerging field.

This general thrust has been enhanced by the Industry Strategy Challenge Fund (ISCF) which focused investment on robotics towards its application in extreme environments (space, nuclear, offshore and mining). The Robotics for a Safer World programme funded four use-case inspired hubs which each include research strands for legged robots. The NASA-produced Valkyrie robot has been a flagship platform for the Fairspace hub which is organised from Surrey University with a focus on space applications. Both NCNR and RAIN hubs are nuclear orientated, with quadrupeds seen to carry out gamma radiation mapping on the facilities of the UK Atomic Energy Authority. Finally, the ORCA hub concentrates on the offshore energy sector (Oil & Gas as well as renewables) and has hosted demonstrations on mock-up oil rig platforms carrying out inspection rounds.

FAIR-SPACE

ORCA HUB
Offshore Robotics for Certification of Assets
Remote Safety and Integrity

NCNR
NATIONAL CENTRE FOR NUCLEAR ROBOTICS

RAIN

Figure 1

Four EPSRC/ISCF-funded research hubs have spurred development and deployment of legged robot demonstrator.

4. LEGGED ROBOT RESEARCH ACROSS THE UK

Several UK institutions and industries, have invested in legged robots, either bipeds, quadrupeds, or hexapods. In this section, we will give a brief overview of the robotic hardware that is currently used in the UK and the main research and application areas targeted.

The Edinburgh Centre of Robotics (Heriot Watt University and University of Edinburgh) has been a pioneer in this field within the UK. Their platforms include the ANYbotics ANYmal and Boston Dynamics Spot quadrupeds, as well as the bipeds NASA Valkyrie and Pal Robotics TALOS. The ongoing research at the Edinburgh Centre of Robotics is focused on optimized motion planning for the legged robots.

The Robot Intelligence Lab at Imperial College London has focused on the mechatronics design including the novel SLIDER biped which uses a linear knee actuator.

The Real Robotics Lab at the University of Leeds has been working with various legged robots, from mini-size pipe inspection “wheeleg” robots, to small-size humanoid robots, to middle-size quadruped robots, such as several Unitree Laikago, Aliengo and A1 robots, as well as an ANYbotics ANYmal. Highlights include the use of the Laikago to carry out disinfection operations during the COVID-19 pandemic in Leeds.

The Interface Analysis Centre at the University of Bristol has used the Boston Dynamics Spot for radiation inspection at Chernobyl in collaboration with RACE (part of UKAEA). The Oxford Robotics Institute at the University of Oxford has two versions of the ANYbotics ANYmal quadruped-model B and C, a Boston Dynamics Spot and a Unitree A1 quadruped robot. This group works on motion planning and navigation targeting challenging terrain and remote facilities. In 2021, they competed in the DARPA Subterranean Challenge as the only UK involvement.

The University of Manchester's robotics group has developed their own custom hexapod robot for nuclear inspection. The University of Plymouth (Centre for Robotics and Neural Systems) used the NAO bipeds and custom humanoid robots in teaching. University College London is working with several legged robots including Unitree A1, Go1, and B1, ANYbotics ANYmal, and Boston Dynamics Spot, as well as DeepRobotics Jueying Lite2 in several application, such as enabling natural sampling of volcanic environments.

In addition to research activities, researchers from the UK also organise international workshops on real-world locomotion, for example, at the IEEE International Conference on Robotics and Automation (ICRA) conference[1].

[1] http://leggedrobots.org

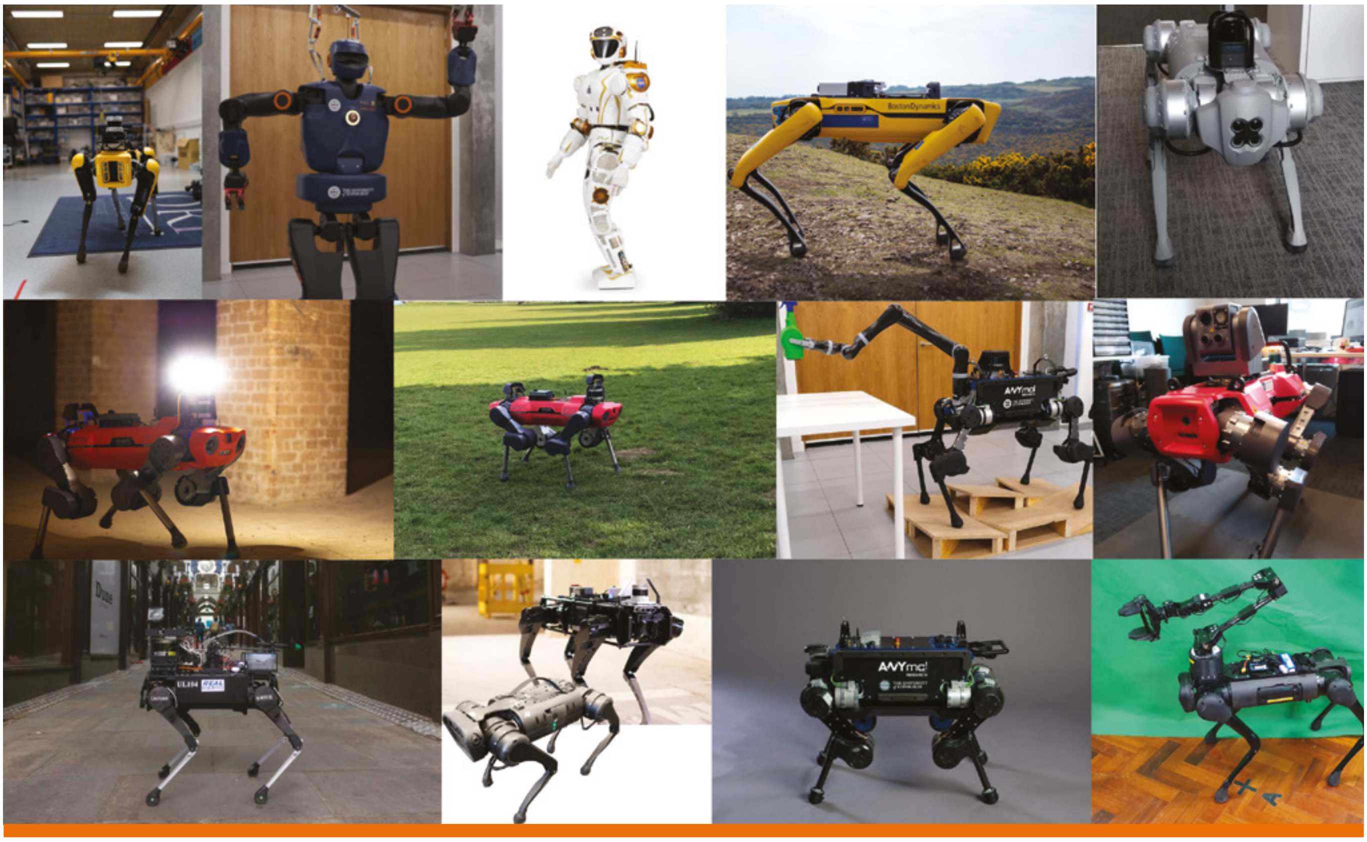

Figure 2

Legged robots from across the UK: University of Oxford, University of Leeds, Edinburgh Centre of Robotics, and University College London.

5. RESEARCH EXCELLENCE ACROSS THE UK

5.1 OIL AND GAS FACILITY INSPECTION

With the combination of high value assets and expensive access, the offshore sector is a logical place for the deployment of legged robots. The ORCA Hub (Offshore Robotics for Certification of Assets) is a multi-university research hub developing technology across this sector —with projects spanning aerial, topside and terrestrial. The University of Oxford and University of Edinburgh have been developing monitoring and inspection as well as intervention capability using the commercially available ANYmal quadruped.

ANYmal, made by the Swiss-based ANYbotics, is a rugged and IP-67 quadruped which has been developed through four generations. The robot now boasts 4 cameras (to map its local vicinity), an automotive LIDAR (for positioning) as well as 12 identical torque-controlled motors on its four legs, that make the robot capable of climbing stairs.

Oxford's focus is on autonomous navigation and mapping — using the robot to understand its environment, build representations and the deploying inspection missions within them. Particular challenges are the constantly changing lighting conditions on industrial facilities. Edinburgh's research is using the robot to explore robust and haptic-aware locomotion. Balance is solved as a combination of constraints which surmise the physical limitations of the robot, expressing suitable forces on the ground and making progress towards goals. Ongoing research is looking to use the robot to develop loco-manipulation — expanding the robot from a mere observer by using an arm to allow the robot to make interventions.

Challenges of permanently deploying legged robots include full mission capabilities, such as autonomous re-charging, while ATEX certification — to guarantee safety in explosive atmospheres — is part of the open issues. To build confidence and to identify collaborators, ORCA have carried out several capability demonstrators during its programme to engage with industrial partners such as that held in October 2019 at the Blyth Offshore Renewable Energy Catapult.

Figure 3

ANYmal quadruped inspecting the Offshore Renewable Energy Catapult Facility in Blyth. (Credit: ORCA Hub)

5.2 MONITORING NUCLEAR RADIATION

Amongst the most apt applications for legged robot deployment is in the monitoring of radiation in and around nuclear facilities - either active or decommissioned sites. These facilities use standard industrial staircases meaning that modern quadruped robots can be deployed. Where a strong safety case can be made, using robot instead of people is a clear de-risk of these routine operations. The development of autonomy for routine monitoring of radiation is the focus of both the RAIN and NCNR Hubs within the ISCF programme.

A particularly high profile demonstration of this was a trial in Chernobyl by University of Bristol in Summer 2020. The team used a modified copy of the Boston Dynamics Spot robot to monitor the New Safe Confinement structure (the massive building completed in 2019 to enclose Reactor 4) as well as various storage locations for equipment used during the 1986 explosion. The robot was loaned to Bristol by RACE (part of UKAEA) with support of the National Nuclear User Facility (NNUF) loan scheme. Bristol fitted the robot with a series of gamma radiation scanners and used automated path following to build 3D representations of the location of residue radiation (as shown below).

The particular interest in the Spot robot is that its light steps stir up a very small amount of radioactive dust and soil that has been collecting, especially within the reactor 4 sarcophagus, where very few people have been sent due to contamination levels. Any workers sent in are first heavily suited to protect them from the radiation and then subsequently given extended duties away from radiation to balance their annual dose.

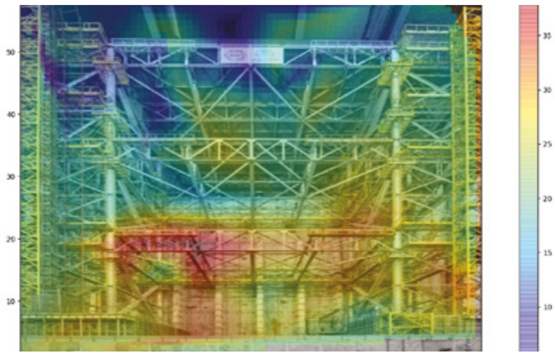

Figure 4

Using the Spot quadruped to monitor radiation at the Chernobyl New Safe Confinement (NSC) structure, Ukraine. (Credit: University of Bristol)

5.3 LEARNING-BASED MOTION PLANNING

A typical walking robot control system includes model-based approaches to footstep planning, trajectory optimization and reflex control. Machine learning is emerging as an attractive alternative to learn complex motor skills. Reinforcement learning research has achieved robust single-skill trotting over unstructured environments. While more recent research from the University of Edinburgh combined multiple skills into a synthesised policy enabling the robot to achieve coherent fall recovery, trotting, and all dynamic transitions on a real robot.

These neural network based feedback controls were trained in simulation, and then deployed on real robots. Real-world testing demonstrates robustness to scenarios which were not encountered during training. Such Sim-to-Real transfer used to be a major stumbling block, but has gradually been overcome by including domain randomisation, more complicated policies and more detailed robot models in the learning process. This improves the robustness of the learning-based policy allowing it to tolerate a certain amount of discrepancies during real deployment.

Research from the University of Oxford has focused on combining reinforcement learning with optimal control. With this approach, learning is still performed in a physically-realistic simulated environment, that progressively becomes more challenging, while Sim-to-Real problems are alleviated by learning an approximation of the robot's motor dynamics in a data-driven fashion.

Other research has used Variational Auto-Encoders (VAEs) to learn a motion representation that can be used to generate situation-specific motion trajectories very fast, while another VAE-based work has focused on creating a low-dimensional latent space, representing the robot's state space, and generating continuously varying walking motions with only a few inputs. The cutting-edge methods of artificial intelligence and deep learning are still in the research stage, with new breakthroughs every day. Different fields of machine learning, common tools and technologies have been invented and proved to be effective by different research groups

Figure 5

Overlay showing the Jueying quadruped being pushed over, recovering and continuing on its way. (Credit: University of Edinburgh) independently - the phenomenon of 'discovering the same truth' across different research domains.

In a global landscape, machine learning research has accelerated this research topic of movement skills in robotics. The present goal is to achieve the basic movement and operation capabilities of humans using real machines. The primary challenges have shifted to reliability, repeatability and the complexity of uneven terrain locomotion. The latter in particular requires fusion of locomotion strategies with visual mapping technologies.

5.4 TELEOPERATION OF LEGGED MANIPULATORS

Removing humans from harm's way is a common trait of our research field. Several legged robotic platforms have shown great capabilities and robustness in operating in challenging or hazardous environments. In addition, the defence and security communities face risks on a regular basis, as a result of investigation, monitoring, or patrolling. Telepresence in robotics has the potential to provide safe solutions suitable for such scenarios. While full autonomy is challenging to achieve, remote physical teleoperation can be useful in many circumstances.

The Defence Science and Technology Laboratory (DSTL) has been exploring the use of innovative telexistence solutions that would give military personnel, emergency services, or humanitarian workers the ability to operate in hazardous environments without physically being present. The TeLeMan (Teleoperated Legged Manipulator) robot developed by the University of Leeds and University College London explores teleoperating a legged manipulator to tackle this challenge. The system consists of a quadrupedal legged robot with a robotic manipulator, and 3D sensing, as well as a human operator with an inertial-based motion capture bodysuit and virtual reality headset. In particular, TeLeMan aims to understand the capabilities of such a system for defence and security with applications in real-world scenarios. As a proof of the concept, the research team are studying if Explosive Ordnance Disposal (EOD) can be achieved out of line of sight in this manner.

The proposed teleoperative legged manipulator could benefit sectors whose working environments are unstructured, complex or hazardous, where combined superior ground mobility, dexterous manipulation and teleoperative capabilities can improve productivity and significantly reduce the risk to human operators. For instance, EOD or nuclear waste handling and disaster response are typical scenarios used to motive this work. The successful integration of these technologies has also attracted the interest of the Nuclear Decommissioning Authority, where remote legged manipulability is a promising solution to address their core challenges.

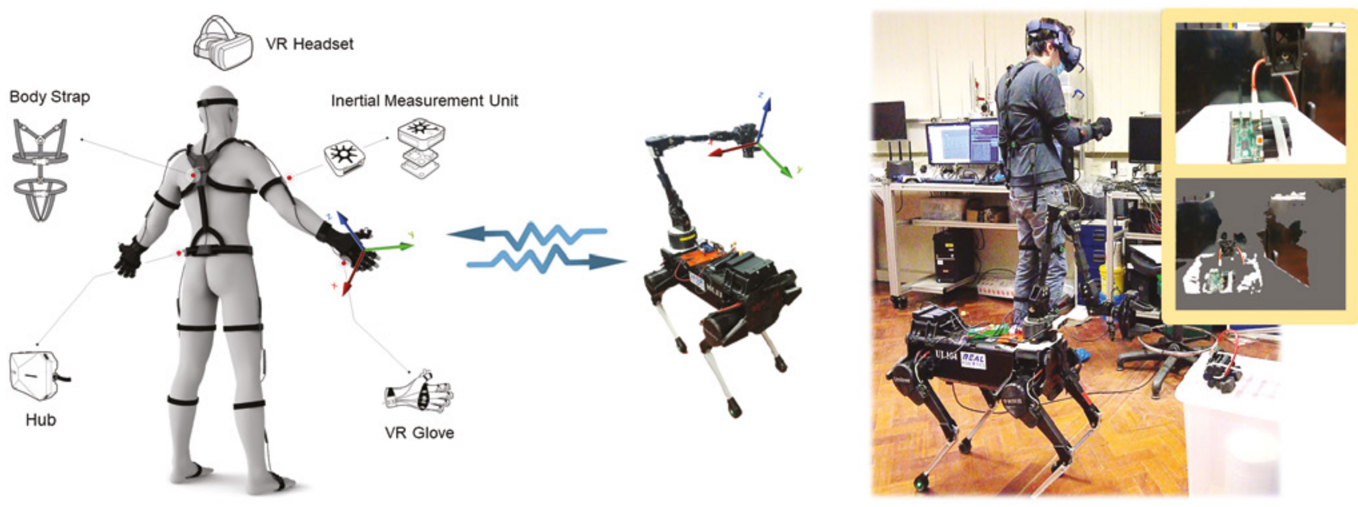

Figure 6

TeLeMan concept (left) and EOD demo (right). (Credit: University of Leeds)

5.5 HUMANOID ROBOTS FOR MANIPULATION AND INTERACTION

Up to this point this report has focused on quadrupeds that have undeniable maturity for field usage. However, operations have been typically limited to passive monitoring and inspection. The full potential of legged robots will require physical interaction with the world and manipulation tasks are becoming increasingly needed.

The full scale humanoids of the Edinburgh Centre for Robotics are the most mature platforms including the TALOS (by Spanish company PAL Robotics) and the Valkyrie humanoid developed by NASA.

Below, the TALOS robot is executing a series of footsteps over uneven obstacles using a combination of optimization and sample-based planning. TALOS is the centrepiece robot of the Memory of Motion (MEMMO) EU research project. MEMMO partners are developing motion harvesting algorithms, compressed with machine learning to provide superior trajectory generation for reactive balance.

In addition, the Valkyrie robot is shown picking a box from a table. The box was first segmented from its background using the robot's LIDAR and camera system. By applying lateral forces and regulating its balance the robot can pick the object from the table. Valkyrie, like all walking robots, continuously redistributes weight hundreds of times per second.

NASA and Edinburgh are collaborating to further develop Valkyrie for possible use in unmanned missions to Mars such as maintaining the Hab (The Mars Lander Habitat) and reducing the cost and danger of external maintenance.

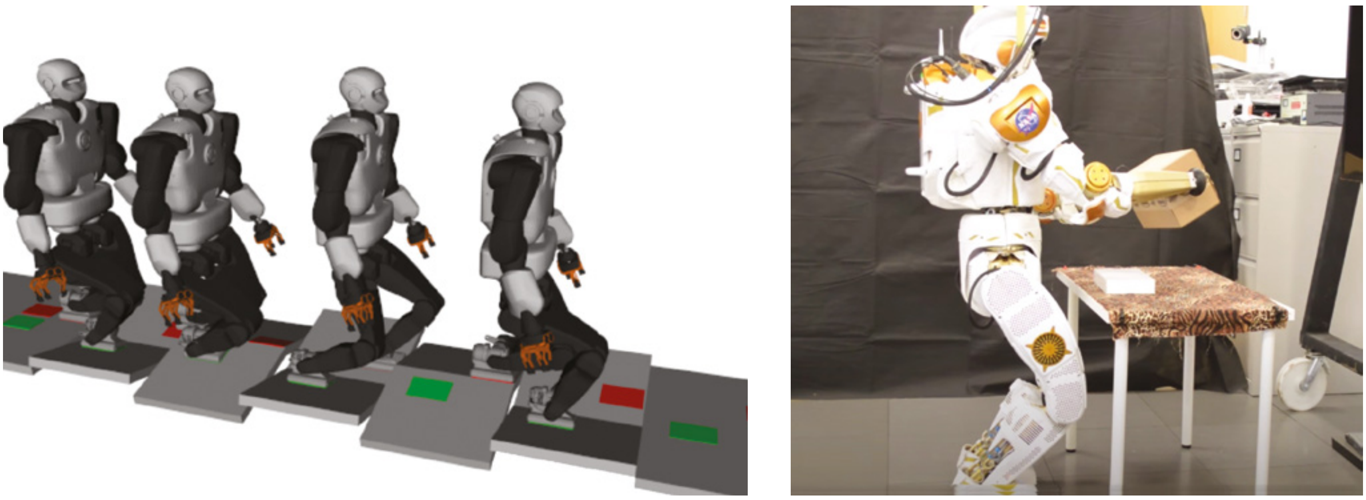

Figure 7

Left: Edinburgh's TALOS humanoid planning stepping on uneven terrain.
Right: The NASA Valkyrie manipulating a box. (Credit: University of Edinburgh)

6. SUMMARY AND RECOMMENDATIONS

This white paper outlined the key challenges and opportunities of developing and deploying legged robotics. We described promising ongoing research across the UK.

Finally, to conclude we offer some recommendations for future directions and investment based on an analysis of existing capabilities including:

- Legged robots now have the attention of major industrial companies. They are being deployed in field trials and have growing credibility in sectors such as power grid patrol, offshore asset inspection and maintenance. Enabling researchers to develop industrial use cases is essential. Focused industry/academic projects should be funded to achieve this.
- Platforms and hardware are expensive, and technology ages quickly. The average life cycle of a new technology in legged platforms is about 3-5 years. In order to place the UK at a competitive global position, the UK funding agencies needs to ensure there is sufficient funding support to renew equipment and to retain engineering and research staff for maintaining platforms, building and enhancing expertise.
- The UK legged robotics community would greatly benefit from an integrative effort to bring together the research groups mentioned above to create more cohesive and science-based progress. This would in turn drive industrial applications. A multi-institute project or programme grant can catalyse such development significantly and increase the international standing and competitiveness of the UK research community.

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