UK-RAS White papers

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ROBOTICS & AUTONOMOUS SYSTEMS

Robotics and Autonomous Systems for Environmental Sustainability: Monitoring Terrestrial Biodiversity

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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 opportunities for Robotics and Autonomous Systems (RAS) to transform biodiversity monitoring. Biodiversity conservation has never been more critical than it is now in the face of numerous threats, not least with climate change, pollution, diseases, etc. As humans, we depend on and benefit from ecosystems that are fully functioning. But how can we monitor species efficiently and effectively? We have already seen the exciting potential that RAS offers for monitoring in marine and aerial environments. Terrestrial environments present particular challenges when trying to collect data at scale and at a community-based level across species. RAS could overcome some of the current drawbacks in terrestrial monitoring, but we need a better understanding of how best to deploy RAS in often extreme environments. I hope this excellent white paper will enable research and development to ensure the UK can benefit from the positive transformation offered by robots that can monitor terrestrial environments in a sustainable way.

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!

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EXECUTIVE SUMMARY

It is critical to protect Earth's biodiversity, not just for its own intrinsic value, but also for the ecosystem services it underpins. Yet biodiversity is in crisis, with up to 1 million animal and plant species at risk of extinction, many within decades. This dire projection has captured world attention and triggered major mitigation efforts, but we are faced with problems in assessing global trends in biodiversity – which species, taxa, habitats and ecosystems are suffering the greatest declines? Are current mitigation measures having any positive impact? To answer key questions such as these, ecologists are seeking the help of robotics and automated systems (RAS) experts in the monumental task of attempting to monitor the state of biodiversity.

In this White Paper, we have surveyed recent literature and consulted more than 120 international expert ecologists and engineers working in the fields of biodiversity and robotics. We have done this to evaluate the potential for developing robotic and autonomous systems that could massively extend the scope of terrestrial biodiversity monitoring across habitats globally. The complexities of biodiversity itself, and the many barriers and challenges that must be overcome in monitoring it, are formidable. We assess each of these barriers in turn, highlighting currently available RAS solutions, as well as nascent technologies that may be relevant to future RAS for biodiversity (RAS-BD) monitoring. Using this information, we have drawn up a roadmap of actions needed to address the barriers that should be easiest to overcome. Encouragingly, we find that a variety of existing RAS capabilities may be transferable to a biodiversity monitoring context. Beyond these are the harder barriers, where promising novel ideas being researched at UK universities and research institutes may, in time, become integral parts of future RAS-BD monitoring technology. We believe that RAS-BD technology has great potential to complement and considerably extend the field survey work undertaken by expert human observers.

In the UK, we are fortunate in having particular strengths in both biodiversity and robotics research; as a nation we are in an ideal position to integrate them and become a leading force in the development and application of RAS-BD monitoring. To this end, we propose these recommendations that we hope will guide future government strategy in an area that is vital to the future of humanity:

- The creation and funding of an integrated multidisciplinary task force, including academics and industry specialists with expertise in RAS and biodiversity, to support technological research and development.
- Future UK funding and focus should be prioritised to utilise existing RAS capabilities to develop first generation RAS-BD technology for monitoring biodiversity.
- Relevant nascent technologies being researched by numerous UK academic teams need increased and accelerated research and development funding to turn pioneering concepts into enhanced RAS-BD technology suited to overcoming the hardest monitoring barriers that ecologists encounter.
- Education strategies should be developed to foster links between aspiring engineers, biologists and computer technologists, both in the curriculum of schools, and at later stages in universities and research facilities.

> The opportunities for RAS to transform terrestrial biodiversity monitoring, and therefore the future of conservation, are huge. Yet, to date, the role RAS could play in surveying species has received relatively little research attention. Furthermore, where robots are used in ecology, it is primarily in marine and aerial environments, rather than terrestrial.

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> “Increasingly, we need to understand how ecosystems are responding to the pressures of climate change, habitat loss and degradation, exploitation, chemical and light pollution, and invasive species. Gaining this knowledge would provide a better understanding of the complex interwoven relationships between ecosystem functioning and human social and economic systems.”

> “If RAS-BD technology could monitor just 10% of species at appropriate scales and time periods, it would be a significant improvement on current methods.”

GLOSSARY

Artificial intelligence (AI): a field of computer science focused on the ability of machines to perform complex cognitive tasks

Biodiversity: the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part; this includes diversity within species, between species and of ecosystems (Convention on Biological Diversity definition)

Classifier: a software tool used to assign identification labels (e.g., species labels) automatically from data such as acoustic recordings and images

Convolutional neural network (CNN): a type of deep learning algorithm most often used for image processing

COTS: commercially-available ‘off the shelf’ products

Data augmentation: a process of generating new data points to increase the size and diversity of an existing dataset

Data mules: vehicles that physically carry data storage devices between locations to create data communication links

Deep learning (DL): a neural network with more than three layers

Drone: an unmanned aerial vehicle that is guided remotely or can navigate autonomously

Ecosystem functions: the physicochemical and biological processes that occur within ecosystems

Ecosystem services: the ecosystem functions that directly benefit human well-being (e.g., the supply and purification of drinking water and the air we breathe)

Ectotherms: cold-blooded animals, whose regulation of body temperature is dependent on external sources such as sunlight or warm/cold environments

Edge AI: implementation of artificial intelligence in a local computing environment (i.e., AI computations are done at the edge of a given network, usually on the device where the data are created, instead of in a centralized cloud computing facility or offsite data centre)

Endotherms: warm-blooded animals, which can generate and control internal heat to regulate their body core temperature

Environmental DNA (eDNA): traces of species’ DNA found in the species’ environment (air, water, soil)

Few-shot learning: a machine learning technique in which AI models learn from a small set of labelled training data

Infrared (IR): infrared light in the μm wavelength range

LED: light-emitting diode

LiDAR: ‘light detection and ranging’, a pulsed laser system that uses reflected μm-nm wavelength light to create maps of distant surfaces

Machine learning (ML): a sub-field of artificial intelligence that enables systems to detect patterns in data and adapt autonomously, typically by analysing large volumes of data

Microbial fuel cells (MFC): fuel cells that generate electricity through anaerobic oxidation

PIR: a passive infrared sensor that detects 7-14 μm wavelengths emitted by warm objects

RAS: robotics and autonomous systems

RAS-BD technology: RAS that are optimised for monitoring biodiversity

Soundscape: the acoustic environment, including all biological, environmental and human-made sounds at a given location

Taxon (plural taxa): a population, or group of populations of organisms, which are inferred to be phylogenetically related and which have characteristics in common that differentiate the unit from other units

UAV: unmanned aerial vehicle, which can be a hovering drone or a fixed-wing aircraft

UGV: unmanned ground vehicle, a robotic system that operates on land

Wireless sensor network (WSN): a network of spatially-dispersed sensors wirelessly connected to a central location

INTRODUCTION

The current rate of biodiversity loss across the planet is profound. In 2019, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) stated that we are facing the extinction of up to one million species globally over the coming decades[1]. Consequently, the agreement arising from the Convention on Biological Diversity Conference of Parties (COP15) in Montreal in December 2022 has been described as the “last chance” to put biodiversity on a path to recovery[2]. It is critical to protect biodiversity, not just for its own intrinsic value, but also for the ecosystem services it underpins. One fundamental issue that biodiversity conservation faces is monitoring species and habitats effectively.

Effective biodiversity monitoring is critical to meeting Sustainable Development Goal (SDG) 15 ‘Life on Land’, and many other SDGs also depend directly or indirectly on healthy functioning ecosystems. However, terrestrial biodiversity monitoring is very difficult to do comprehensively using existing methods and resources. The first challenge is that it is time consuming and expensive to replicate spatially and temporally. Surveys normally take up a substantial amount of time per site, with 10s or 100s of sites needing to be surveyed and done so repeatedly. This is exacerbated by the need to have differently skilled people on site to survey different taxonomic groups (e.g., bees, frogs, bats, birds, reptiles, trees). Species often have restricted niches (places where they can survive), meaning that the effectiveness of monitoring is severely hampered or biased by environmental factors (e.g., sites/niches that are inaccessible and/or dangerous for humans, extreme abiotic conditions such as temperature, humidity and precipitation). For instance, scientists still have a very limited understanding of what species inhabit tropical rainforest tree canopies because they are so difficult to access. Most of the knowledge we do have has been acquired by destructive sampling (e.g., fogging arthropods in the canopy by using a non-persistent insecticide).

Human surveyors can also disturb or overlook cryptic, elusive, small, or specialised species. RAS offers the potential to overcome some of these challenges. It could facilitate data collection over large spatial and temporal scales, with variable areal resolution (‘granularity’) and time frames, to assess communities of species more comprehensively. The opportunities for RAS to transform terrestrial biodiversity monitoring, and therefore the future of conservation, are huge. Yet, to date, the role RAS could play in surveying species has received relatively little research attention. Furthermore, where robots are used in ecology, it is primarily in marine and aerial environments, rather than terrestrial.

The project behind this White Paper began with a literature review to identify the methods used by ecologists to monitor terrestrial biodiversity, and the major barriers they encounter in performing this work. This was followed by a consultation process involving online surveys and workshops during May and June 2023, in which over 120 international experts in biodiversity and RAS took part. Using these inputs, we have developed a roadmap indicating how RAS could transform the complex and often arduous work involved in monitoring diverse taxa (across plants, animals, fungi) in a wide range of habitats. We highlight where existing RAS capabilities are aligned with biodiversity monitoring requirements, how these capabilities could be extended, and the priorities for future RAS developments.

PART 1

1.1 WHAT IS BIODIVERSITY?

The term 'biodiversity' has various popular meanings, such as 'the variety and abundance of the world's plants, animals and fungi'[3]; 'the sum of all life on Earth'[4]; and 'all the different kinds of life you'll find in one area'[5]. It also has a much wider meaning, describing not just species, but the inter-relationships between all forms of life, their environments and their habitat niches[2]. Terrestrial biodiversity is measured at many levels across the plant, animal and fungal kingdoms: individual organisms, species, communities and entire ecosystems. Biodiversity is found in all global regions, including habitats with extremes of ambient temperature, precipitation, humidity, light level and altitude. It is more diverse in the tropics, where there are the most species, and more complex ecological interactions[6]. However, alkaline lakes, volcanic mountains, polar icecaps and deep caves are all rich in specialised lifeforms.

In this White Paper, we focus on eleven major taxonomic groups (Fig 1). We excluded microscopic organisms (e.g., bacteria and algae), which are difficult to incorporate into the traditional paradigms of biodiversity. However, these microbes play a crucial role in the Earth's nutrient cycle, for example by decomposing organic matter and maintaining the health of soils that host the food chains that support humanity and other biodiversity. In addition, through photosynthesis, carbon fixed by soil algae equates to about 6% of the primary production of all terrestrial vegetation[7]. Potential methods of using RAS-BD technology to monitor microbes are noted in section 2.6.

Although over 1.8 million terrestrial plant, animal and fungal species have been classified and catalogued by taxonomists, an estimated 86% of species in these kingdoms still await formal description[8]. Within some taxa, the number of 'unknown' species (i.e., those known to exist, but not yet described and given a scientific name) dwarfs that of their 'known' counterparts. Across all taxa, new species are constantly being discovered. As an example, in May 2023, research in just one valley in Asia revealed 380 new species, including 290 plants, 46 reptiles, 24 amphibians and one mammal[9].

Arthropods are by far the largest taxon, with over 1.2 million species described. It is estimated that there are up to 7 million extant species of this diverse group that includes all insects, flies, spiders, ants, butterflies, crickets, beetles, millipedes, crustacea (e.g., woodlice, terrestrial crabs) etc.[10]. Plant and fungal species are also very numerous: around 369,000 species of vascular flowering plants[11](which exclude algae, mosses and liverworts), and over 150,000 species of fungi have been described to date[12]. The actual number of fungal species may be at least an order of magnitude higher: recent DNA sequencing evidence based on host association suggests that there are 2.2 – 3.8 million species of fungi[12]. Scientists estimate that there are ~73,000 tree species, of which ~9,000 species (mainly in South America) are yet to be described[13]. Molluscs (e.g., slugs, snails) and annelids (e.g., earthworms, leeches) are next, with ~35,000 and ~22,000 species respectively[7]. Following these five taxa, and with far fewer species, are the taxa that are most familiar to most people: reptiles (~11,900)[14], birds (~11,000)[15], amphibians (~8,700)[16] and mammals (~6,400)[17], of which ~1,400 are bats. We have separated trees from other plants, and bats from other mammals, because different monitoring methods (section 1.2) are suited to these different groups.

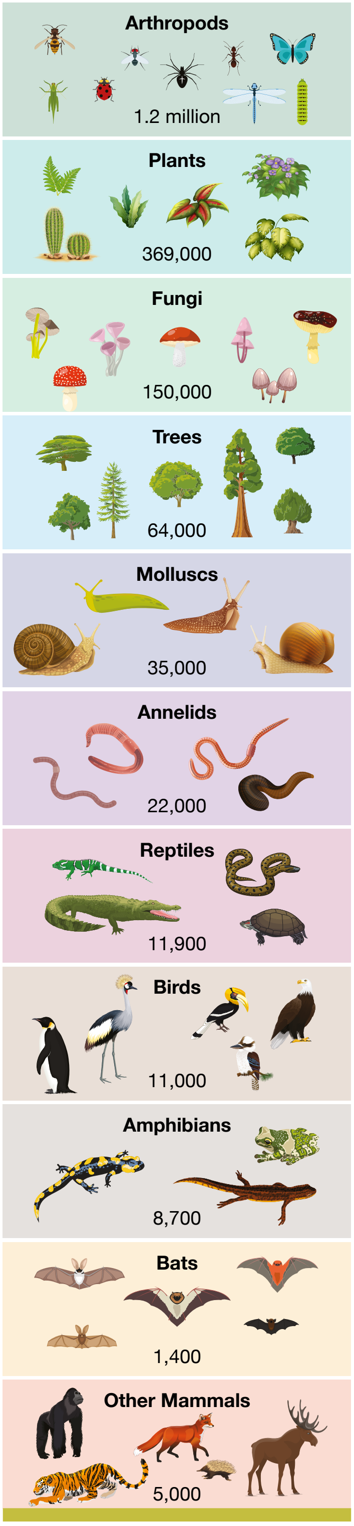


FIGURE 1:
Approximate numbers of extant described terrestrial species in the major taxonomic groups

Biodiversity is monitored in order to gain insights into the state of ecosystems across a diverse range of habitats globally. By identifying species of all taxa, monitoring trends in their populations, and observing their behaviour, we build up our understanding of how 'healthy' our ecosystems are. Increasingly, we need to understand how ecosystems are responding to the pressures of climate change, habitat loss and degradation, exploitation, chemical and light pollution, and invasive species. As society attempts to mitigate many of these drivers of biodiversity decline, we need to monitor how ecosystems respond to our actions, whether they are human-dominated urban areas or, at the other extreme, remote wilderness. Gaining this knowledge would provide a better understanding of the complex interwoven relationships between ecosystem functioning and human social and economic systems.

Many species have subterranean homes. Above: in the Kalahari Desert, southern Africa, tiny male barking geckos (left) plug their burrows during the day and emerge at dusk, whereas ground squirrels (right) are generally active during the day. Below: hairy armadillos (left) in southern Chile are mainly nocturnal and live in complex deep burrow networks. Andean flickers (right) are a diurnal species restricted to altitudes above 3500m in the Atacama Desert.

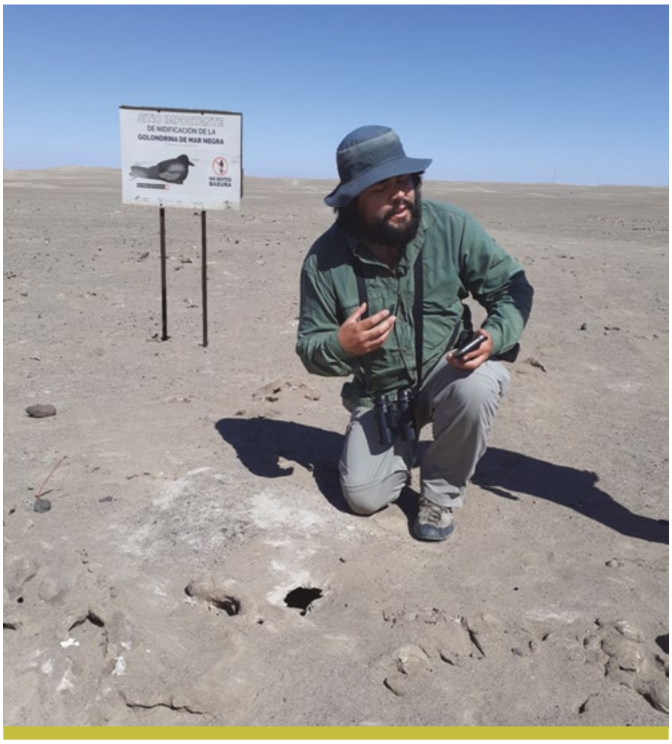
1.2 MONITORING TERRESTRIAL BIODIVERSITY

Accurate identification of 'known' species requires considerable expertise in field observation and, for some taxa, detailed knowledge of taxonomy. Until recent decades, biodiversity monitoring of many terrestrial taxa was largely carried out through visual and/or sound surveys along transects or at fixed points within habitats. For subterranean annelids, digging and hand-sorting soil to identify species and estimate abundances is the most widely used method. Surveys might also be supplemented by various forms of trapping, such as mist-netting for birds and bats, and live traps for small mammals. Amphibians and reptiles are generally captured in pitfall traps or within/under artificial refuges. The many methods for trapping arthropods include sweep netting, beating trays, Malaise- and light traps, pan traps and lighted suction traps.

Numerous additional monitoring methods have been adopted as technology has developed. Tripwire-based camera traps for recording wildlife date from the 1890s, leading on to cameras triggered by interrupted light beams in the 1960s[18]. For many decades, large mammals (e.g., elephants, giraffes, ungulates) and certain large species of birds (e.g., flamingos, waterfowl) have been monitored by trained observers within aircraft[19]. Satellite imagery was first employed in the early-1980s for large-scale assessment of trees and vegetation. More recently, this method has been used to estimate penguin abundances at inaccessible colonies in the Antarctic[20]. From the late-1980s, ground- or aircraft-based pulsed laser light detection and ranging (LiDAR) technology has been used to measure tree density, canopy structure and leaf area, and to monitor changes in tree- and forest quality[21].

Another technique dating from this period is the genetic analysis of DNA fragments left behind by species in their environment, defined as environmental DNA (eDNA). First used to detect and describe microbial communities in marine sediments in the mid-1980s[22], laboratory-based eDNA analysis is now widely used[23] to detect the presence of species (e.g., non-destructive sampling of arthropods[24]). This powerful technique has some limitations, such as biases[25], and determining species' abundances[26]. In addition, in areas where many undescribed species are present (e.g., the Amazon Forest), detection is only possible at species' group level. Nevertheless, even at this level, using eDNA to detect biodiversity across a wide range of taxa is an invaluable tool.

An ecologist undertaking a transect survey in Zimbabwe using a laser rangefinder and binoculars.



Markham's storm petrel nests underground in saltpetre cavities in the Atacama Desert up to 25 km from the Pacific Ocean. This marine species only visits the nesting grounds at night and scientists use night-vision binoculars, supplemented by passive acoustic recordings, to monitor their populations.

Since the early-1990s, bioacoustics recordings by passive acoustic recorders have been used as a way of identifying some vocal, but difficult to observe, species such as grasshoppers and amphibians[27]. Nowadays, they are also a major tool used for detecting and identifying bats and birds.

Over the past twenty-five years, major technical developments in digital photography, sensors, drones, artificial intelligence (AI), smart phones, battery technology and wireless networks have further transformed the methods ecologists use to survey biodiversity. Camera traps with passive infrared motion sensors are now routinely used to record visual and infrared wavelength images across a wide range of taxa and habitats. These can be mounted in fixed positions, or carried by drones, which can also carry passive acoustic recorders[28] and environmental sensors[29]. The use of more advanced RAS monitoring techniques is a recent trend; between 1992 and 2012, only 10 of ~100,000 scientific papers related to robotics appeared in the top twenty ecological journals[30]. A similar search for the period 2013 to 2022 revealed 116 of ~406,000 papers, 71 of which have been published since 2020[31].

The wide availability of low-cost, high-resolution, digital cameras has resulted in ‘citizen scientists’ helping to create extensive databases of images of common species of most taxa. In addition, large libraries (e.g., Xeno Canto[32]) have been created of bioacoustics recordings of vocal species of several taxa. Many of these libraries are open-access, and their data, coupled with advanced image and sound recognition capabilities of AI software, have been used in numerous smartphone-based species recognition apps (e.g., BirdNET[33] and Merlin[34] call identification for over 3,000 bird species, PlantNet for 37,300 plant species[35], iNaturalist[36] for 5,000 plant and animal species, etc.). Most of these apps have been developed over the past decade, with their identification accuracy improving considerably through time. It is, however, important to note that these apps are focused on the more common species of ‘easy’ taxa that are of the most interest to the public such as mammals, birds, butterflies, plants and trees (i.e., which are generally large and/or charismatic, but which represent <5% of all terrestrial species).

PART 2

2.1 RAS FOR BIODIVERSITY MONITORING

Climate change, and the potential impacts of moves towards 'net zero' (e.g., the establishment of large wind and solar farms), have given a new urgency to tracking biodiversity trends worldwide. Increasingly, capital funding of industries and business sectors is focussing on investments that prioritise positive outcomes for biodiversity, or do not actively contribute to its degradation[37]. Measuring such outcomes is a major challenge, and it is clear that step changes are needed in the methods used to monitor species' populations across all taxa, with new ways of sensing, assessing and reporting on them. Existing methods used by ecologists are severely limited by the many barriers and constraints they face in carrying out field surveys. By using questionnaires and online workshops, involving more than 120 international experts in the fields of biodiversity and RAS, we investigated the key practical barriers encountered alongside potential RAS solutions. Four broad categories of barriers emerged: i) access to, and within, survey sites; ii) sensor capabilities; iii) data handling; and iv) power/network requirements.

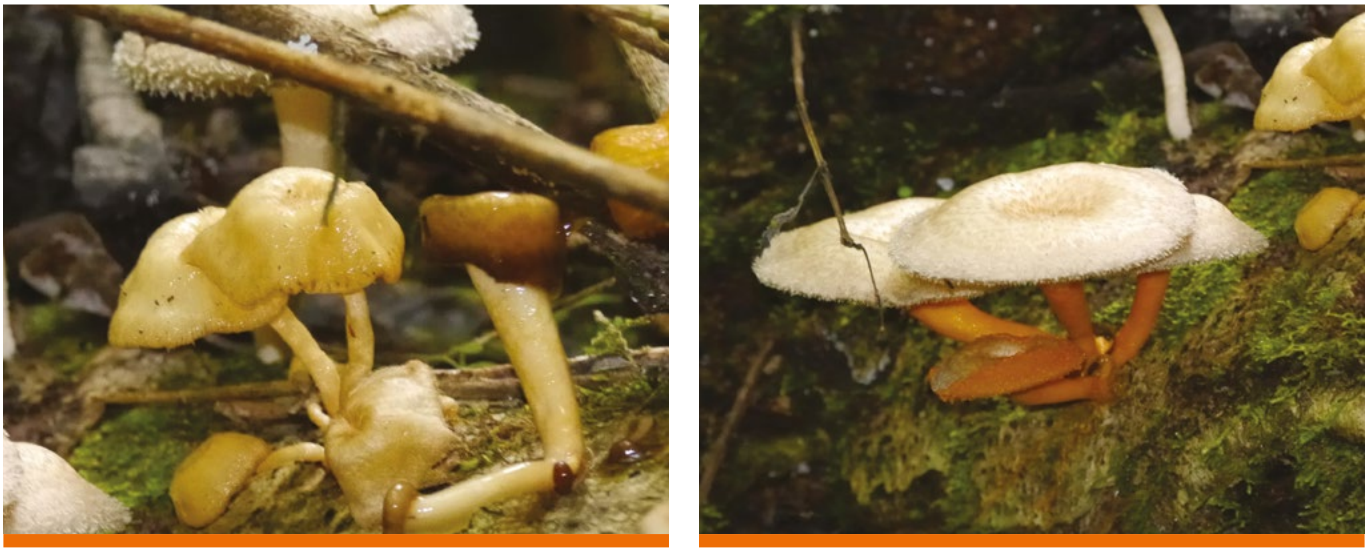
The first barrier to overcome is often human access within certain habitats, which can be difficult, dangerous or even impossible. The widespread application of existing RAS technology to navigating through hazardous and structurally complex areas (e.g., nuclear facilities, underground pipe networks, orchards on steep hillsides) suggests that this barrier may be overcome using similar solutions. However, access in itself is only a first step.

RAS platforms need to be equipped with powerful sensors to detect target taxa, and the second barrier - sensor capability - is where the problem becomes more complex. Terrestrial vertebrates (mammals, birds, reptiles, amphibians) range in body size from ~8 mm to ~11 m[38], they can be diurnal or nocturnal, and either endotherms or ectotherms. Invertebrates (annelids, arthropods, molluscs) pose far greater challenges, being ectotherms and ranging in body size from <<1 mm to 1 m[39]. Plant and tree surveys also pose problems of scale, with species-level identification in some plants being dependent upon almost-invisible microscopic features, while giant redwood trees can reach over 80 m in height[40].

Matching the monitoring skills of an expert human observer is a formidable challenge as it is estimated that the human senses generate 1 - 2 gigabytes per second of data through sight, hearing, smell, touch and taste[41]. Thus, it is possible that during a one-hour period of field observations, an ecologist's brain may be processing 3.6 - 7.2 terabytes of data in attempting to identify and quantify the species present. To varying extents for different taxa, all of the human senses may be utilised by expert ecologists in carrying out field surveys. In addition, these experts have had years of training and experience of observing taxa and individual species.

The third category of barrier is data handling. Ecologists may need to survey biodiversity over periods of days, weeks or even months, often in places that are remote from infrastructure. Over these periods, powerful sensors can record large volumes of data very quickly, rapidly exhausting onboard memory capacity. Data transmission to cloud storage for subsequent off-line processing may be possible if a suitable communication network (e.g., 4G/5G broadband, satellite facility, etc.) is present. Alternatively, onboard data processing using AI offers a potential solution. However, in both cases, the energy required comes up against the fourth barrier, which is power. Batteries carried by RAS devices need to power the robotic movement, the sensor(s), and the controller with memory storage; the endurance of battery powered unmanned aerial vehicles (UAVs) is typically up to 30 minutes before needing recharge[41].

For each of these barriers, we assessed both the current capabilities of RAS to overcome the challenges and, where RAS solutions do not exist, identified areas of cutting-edge research that may offer potential for developing appropriate RAS-BD technology. These barriers are discussed in more detail in the following sections.



Access to sites, and the ephemeral nature of fungi, make them difficult to study. Their crucial role in decomposing plant and animal debris facilitates nitrogen fixation and phosphorous mobilisation that are essential for plant development. This undervalued taxon also performs a carbon sequestration service, capturing atmospheric carbon and storing it in the soil for decades.

2. 2 ACCESS FOR SURVEYS

There are many barriers to access for monitoring biodiversity. For example, difficulties in accessing large areas for rapid and comprehensive surveys; repeated sampling over multiple seasons and years; and simultaneous sampling of multiple sites. Biodiversity experts who participated in our workshops explained why these latter types of surveys are crucial:

"…repeated sampling/monitoring is needed when seasonal variation is important, for example, at higher latitudes…"

"Sampling multiple locations simultaneously is important for taxa whose activity may be especially weather-dependent"

However, RAS-based surveys over long periods are also expected to be particularly challenging:

"This overall topic is likely [to be] the biggest frontier in RAS as most electronic systems need much maintenance and upgrades"

Even in habitats that pose few problems for human access (e.g., grasslands, savannah), large-scale biodiversity monitoring programmes are generally impractical because of the limited availability of trained experts. Numerous habitats encompass areas that are hazardous to access (e.g., canopies in tropical forests), impenetrable (e.g., dense scrub, reedbeds, thick forest) or inaccessible (e.g., cliffs, marshlands, agricultural crops). The personal safety of ecologists undertaking field surveys may be threatened in some politically unstable countries, and theft or vandalism of monitoring equipment is a universal problem.

Species of some taxa occur in awkward or complex habitats, such as underground burrows, tree holes or deadwood thickets. Harsh weather conditions are also challenging for field surveys, posing problems for both humans and their equipment, which can fail in extreme heat, cold, rain, high humidity and strong winds. An expert working in the tropics reported that:

"In west central Africa we struggle with lightning strike damage on static electronic equipment".

Currently available RAS capabilities may offer potential solutions to overcome some of these access challenges: specialised UAVs or UGVs operating independently, or as swarms; robots for pipe and tunnel inspection; data-mule drones that drop-off/collect wireless sensor network pods without mobility; drone-borne aerial manipulators; 'snake arm' endoscopy for hole access; and 'field' legged robots with dust and water ingress protection.

Other RAS developments at early stages are: soft robots for crawling through crevices; tactile feedback for terrestrial robot navigation; tree-climbing robots; soft biodegradable robots for top-soil monitoring; agile UAVs with visual navigation capability; and 'drone in a box' solutions for repeated sampling over long periods.

Nonetheless, the requirement that disturbance to the ecosystem (taxa and habitat) caused by robot-mounted sensors should be no greater than that resulting from human field survey procedures was viewed by RAS experts as a difficult problem to overcome:

"…aerial vehicles are noisy and many wheeled terrestrial vehicles can be destructive in terms of trampling".

2.3 SENSOR CAPABILITY

The capability and performance of on-board sensors mounted on robotic platforms will be paramount to the success of using RAS for monitoring biodiversity. Biodiversity sensing techniques that are already in widespread use are: passive acoustic recorders, digital visual cameras, passive- and active infrared cameras, hyperspectral cameras, LiDAR and centimetre-wave radar. For future fully automated monitoring, RAS-mounted sensors will need high spatial resolution and sensitivity to distinguish individuals within groups, to detect small taxa, and to identify cryptic species at a distance.

Our workshop for biodiversity experts identified the ability to detect and identify small individual animals and plants, even in low light levels, as being especially important, but also difficult to achieve, with comments such as:

"… this would be amazing as it would allow measurements of population trends over time".

"Nocturnal ecology is a huge gap! Pollination is a good example".

"May be limited applicability for plant species – sometimes need to identify from very small features".

Ideally, sensor design, operation, and control should be simple and eliminate the need for multiple devices, each specific to different taxa, habitats and seasons. Sensors must also be robust to withstand interference from species, and offer resilient operation and durability in all macro- and micro-environmental conditions. Coping with harsh environmental conditions and extending RAS sensor capabilities beyond today's commercial off-the-shelf (COTS) products are recognised as significant challenges. Comments from RAS experts in our workshops confirmed problems experienced by biodiversity experts when using currently available monitoring equipment in harsh environments:

"…many [C]OTS solutions are not so good at dealing with harsh conditions".

"Most lab-built robots do not have great corrosion resistance".

In terms of extending sensor capabilities, currently available technologies that may be relevant, but are not yet widely used, include: techniques to enhance passive acoustic recorder sensor capability through time-series analysis; sensors developed to identify broad-leaved "weeds" in agricultural grassland; the use of LED/Xenon light flashes in low light conditions; AI-assisted active infrared cameras for recording ectotherms; and techniques to combine imagery from digital and hyperspectral cameras with LiDAR data. Automated collection of eDNA material has recently become possible using newly developed robot-deployed soil probes, robotic arms for liquid sampling, and UAV-mounted air samplers.

Early-stage work on low cost/low power millimetre-wave radar sensors shows promise to extend RAS capabilities, as does 'chemical nose' biohybrid system technology using graphene-based sensor arrays. This latter technology is particularly relevant to the suggestion of one biodiversity expert:

'…alternatively, we could develop sensors that detect other things. We often focus on sight and hearing as those are the senses we most rely on, but what about others, such as smell?'.

2.4 DATA HANDLING

RAS sensors with the capability needed to monitor biodiversity rapidly generate extreme data volumes during extended survey periods. In particular, extracting accurate biodiversity information from passive acoustic recorder data is a complex problem as the recordings contain overlapping sounds from three sources. These are sounds of anthropogenic origin (e.g., vehicles; anthrophony), of environmental origin (e.g., wind; geophony) and of biotic origin (e.g., species; biophony). The full spectrum of all recorded wavelengths must be retained to distinguish between the studied taxa and the background soundscape. The problem that this causes is summed up by a quote from our biodiversity expert workshop:

"Storage for extreme volumes of data is a top priority in the bioacoustic monitoring field. We are drowning in data and many institutions are unable to provide the storage support we need".

Some currently available RAS technologies that could be used to reduce the problem of data volumes are: data-mule robots to collect data from static sensors; 'EDGE' processing (i.e., performing AI computations to pre-process sensor data on the RAS device); AI prioritisation of data storage based on sampling variation; using lossless data compression techniques; and optimising storage through intelligent use of networked sensor data.

The ease of use and widespread availability of image- and sound-based apps, such as iNaturalist, suggests that it may become possible to process data collected by RAS sensors in real time to provide near-instantaneous detection, identification and quantification of species. However, a pre-requisite of automated analysis is a huge library of expert-certified species' images (or sounds) with geographical relevance to train classifier software routines. This poses a particular problem for rare species and under-studied taxa. Care also needs to be taken to ensure that robust analysis incorporating detectability issues is performed on sensor data. Even where species' images do exist, the accuracy of classifier identification is dependent on many factors. For instance, images need to have been recorded from many angles to allow for the random orientation of the RAS sensors with respect to the study subject. Many workshop participants from the biodiversity community commented on this, for example:

"I think this [automated analysis] will be hugely important. The volume of data to process is already a limiting factor for methods like camera trapping, and this is only going to increase rapidly with new techniques and more sensors".

"AI not only can be used during the analysis stage, but also for the methodology as a whole. AI has the promise to act as a revolution. This will go beyond smarter analyses, but probably also interfere with the way we study biodiversity".

"What worries me is that as we build in more and more 'black boxes' we will get more errors that we have no method of identifying".

“Monitoring rare species: I am sceptical that RAS can do this, especially for plants, but also invertebrates. The effort involved is probably greater than for trained surveyors”

One expert expressed concern over the risk of RAS-BD technology diverting funding from traditional field-based conservation work:

“There's a serious risk that funders decide to invest in fairly experimental tech over boots on the ground and for many things we are still a very long way from a technical alternative. Such alternatives are also obscene when taken to countries where the wages paid to field workers and rangers are a pittance”.

Another, quite different, concern was raised regarding apps, AI and library images used by classifiers - that of bias in terms of taxa and species:

“We need to redress biases towards large mammals and birds…it is easier to find an elephant than a gnat… sometimes non-charismatic taxa are considered as such because of the lack of data (contributed by lack of attention), but can be equally as important as charismatic taxa”.

Another participant remarked:

“When discussing these methods there is definitely an element of defensiveness in some responses - some justified but also, I think, a sense that autonomous ID reduces the value of biodiversity expertise”.

There are few current solutions to the challenge of compiling the huge annotated datasets that are needed for automated species identification. Progress in this area will come from the development of more powerful machine learning approaches that employ techniques with reduced data requirements, such as ‘few-shot learning’. An example is the use of limited real data, supplemented by simulated data, to identify large mammal species in camera trap images[42]. However, the misuse of few-shot learning techniques without adequate expert validation can lead to serious misrepresentations of biodiversity[43].

2.5 POWER AND NETWORKS

Power and network availability are major barriers to monitoring biodiversity. The most challenging aspect is power, in terms of both consumption and availability, which hampers the work of ecologists using current tools, such as camera traps. Power limitations restrict the usage of most UAVs to about 30 minutes and ground robots to 1 - 2 hours of autonomy. It was generally recognised by all biodiversity and RAS experts in our workshops that solving the power challenge is crucial for developing autonomous RAS-BD monitoring. While battery technologies have made great strides in recent years (e.g., improved energy density, capacity, weight, lifetime, durability), battery-powered devices with power-hungry sensors have a short operational life before needing recharge. Other barriers are: the weight of power systems; powering sensors where solar power is unavailable; battery performance in extreme temperatures; the environmental impact of used power sources (and all associated end-of-life RAS equipment); and the availability of network connections for data transmission and remote device control.

Several currently available techniques could be used in RAS-BD applications. For example, biodegradable and recyclable soft robotic systems could address many of the environmental impact issues. Improved power availability is offered by high energy-density new battery technologies such as lithium iron phosphate. RAS-mounted solar panels, and homing RAS systems that return to recharging hubs could extend equipment operating times.

Numerous developments are under way to reduce power requirements. These include long-range wireless area networks; low powered microchips; energy-efficient cameras; and perching aerial robots with reduced energy needs. Networks of small, low-energy, sensors linked to powerful central processors offer another solution. Microbial fuel cells that are under development in a number of laboratories promise an alternative sustainable approach to power requirements. Several other ideas for providing sustainable power to future RAS-BD systems were floated by workshop participants: harnessing rain or wind (automated sailing boats being an example); triboelectric energy; and chemical energy.

2.6 UK RAS TECHNOLOGY STRENGTHS: POTENTIAL FOR MONITORING BIODIVERSITY

Although mainly aimed at industrial, healthcare and infrastructure applications, many current robotics research projects at UK universities and research institutes are applicable to developing RAS-BD monitoring technology.

The work of five major UK centres of excellence in robotics and autonomous systems is highly relevant to the biodiversity challenges. The Bristol Robotics Laboratory (BRL) is an interdisciplinary research centre that addresses a wide range of key areas of robot capabilities and applications. The safe interaction between robots, humans and their environments is the focus of research at the Edinburgh Centre of Robotics, while the National Robotarium is a development centre for testing robotics and AI solutions. At the University of Lincoln, the Lincoln Centre for Autonomous Systems and the Institute of Agri-Food Technology have laid many foundations to deploy RAS technology (UGV and UAV) into natural and agricultural environments. These include solutions for soil sampling, automated counting of insects, and the development of holistic biodiversity indexation using computer vision. Experimental robotics laboratories at the Institute for Safe Autonomy, University of York provide test facilities for autonomous systems operating on the ground, underwater and in the air.

Current research at the Universities of Aberystwyth, Bristol, Cranfield, Edinburgh, Edinburgh Napier, Lincoln, Surrey, West of England, and Imperial College on aerial, autonomous, crawling, legged and swarm robotics is applicable to the problems of accessing large survey areas and hazardous or inaccessible biodiversity niches. Heriot-Watt University has considerable expertise over many years in underwater robotics; this technology may be applicable to monitoring amphibian species. Equally relevant is the work of the ‘Pipebots’ academic team, comprising researchers from the Universities of Birmingham, Bristol, Leeds and Sheffield, which is aimed at revolutionising the task of utilities in managing buried pipe networks. Their technology may provide the basic tools to monitor subterranean biodiversity in ways that are more effective and less intrusive than current methods. This would enable a wide range of subterranean taxa to be studied, from large burrowing mammals to earthworms. Extending this further, robotic collection of below-ground eDNA samples, and ‘chemical nose’ detection of unique volatiles, would facilitate the monitoring of microscopic organisms (e.g., bacteria and algae) that play a significant role in the global carbon cycle.

Other crucial areas being researched in UK universities include: sensors (Cambridge, Edinburgh Napier, Manchester, Newcastle, Southampton, Sussex); long-range wireless network monitoring of animal movements (East Anglia); embodied intelligence (Imperial College, UCL); soft robotics (BRL, Bristol, West of England); bioinspired robots (Edinburgh, Imperial College, Leeds, UCL); biodegradable robots (West of England, BRL); and cognitive methods, planning and AI for robotic control (Edinburgh Napier, Heriot-Watt, Imperial College, Kent). Enhanced robotic vision using machine learning (Bristol, Heriot-Watt and Lincoln) is also a key area of technology that will be essential for biodiversity applications. Research into resolving the energy needs of autonomous robots includes the development of microbial fuel cells (BRL), and designs of ultra-low power microchips to prolong battery life (Manchester).

> “Many enabling technologies, fundamental tools and robotic capabilities needed for RAS-BD monitoring already exist in some form. Cutting edge research within the UK robotics community, albeit for other applications, has led to significant progress being made in developing potential solutions to barriers that ecologists encounter.”

PART 3

RAS-BD TECHNOLOGY ROADMAP

The challenges involved in developing RAS-BD monitoring technology range from being fairly easy to achieve in a relatively short timescale to being difficult, very difficult, or unrealistic at present. We propose a roadmap for development that first addresses the biodiversity barriers that would be easiest to resolve, before attempting areas where existing RAS capabilities would need significant technical advances to overcome more difficult challenges

Fairly Easy/Limitations to Overcome

- Remote deployment of RAS-BD monitoring to locations that are hazardous or inaccessible to humans (e.g., awkward, at height)
- Repeated surveys of specified areas over extended periods
- Performing synchronised surveys at multiple locations
- Monitoring biodiversity in low/no light situations
- Sensor data transfer in real time to avoid data loss or corruption
- The ability to remotely control and maintain RAS-BD monitoring devices
- Developing RAS-BD monitoring technologies capable of servicing/emptying species' traps remotely (e.g., insect traps)
- Robotic collection and storage of eDNA samples from some habitats

Difficult

- Accessing distant locations in extreme environments
- Systems that are robust and perform consistently in harsh environmental conditions
- RAS-BD monitoring technologies that are easy to use without engineer support

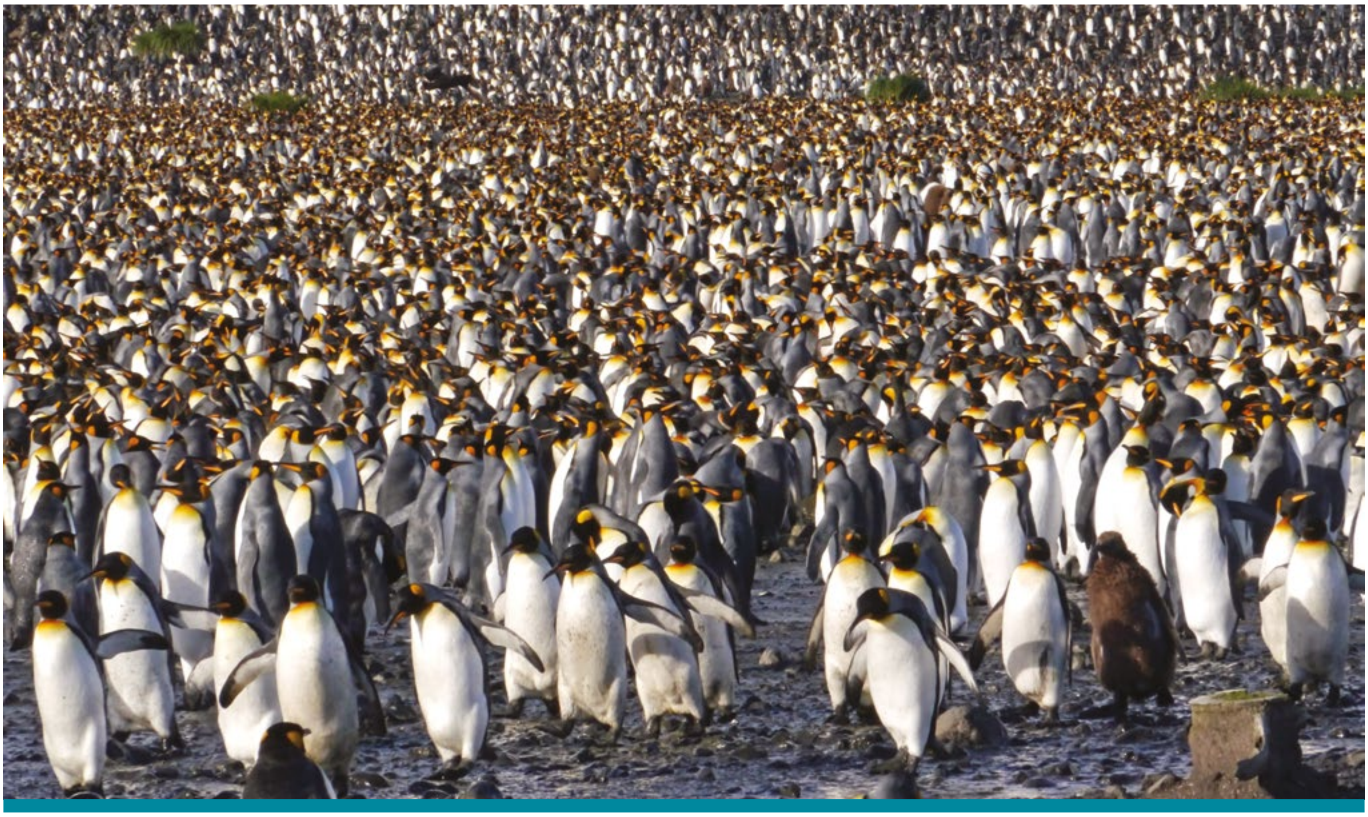
- Implementing methods to deal with extreme data volumes generated by sensors
- Reducing power requirements and the weight of power systems
- Reducing the environmental impact of e-waste associated with RAS-BD monitoring

Very Difficult

- Autonomous systems for surveying multiple taxa over large areas
- Surveying structurally complex/restricted habitats (e.g., burrows, beneath ground/snow) with minimal disturbance
- Reducing the need to remove samples for analysis
- Identifying individuals of small species from a distance
- Guaranteeing that species are detected when present
- Monitoring multiple taxa, across the whole range of species sizes, habitats, and environmental condition extremes with few sensors
- Designing RAS-BD monitoring technology for assessing diverse ecosystem functions and processes (e.g., pollination, predation, decomposition)
- Energy harvesting to produce enough power for RAS-BD technology

Unrealistic at Present

- RAS-BD monitoring that causes no disturbance to species or their habitats
- Designing RAS-BD monitoring technology that is biodiversity, weather, vandal and theft-proof
- RAS-BD monitoring technologies that can communicate through all barriers
- Accurate automated identification from sensor data containing tens of thousands of species and individuals
- Developing AI systems to correctly identify poorly-known, rare, elusive and difficult taxa, or life history stages
- Intelligent control systems to enable RAS-BD monitoring technology to know where best to be located for surveys and identification



3.2 CONCLUSIONS AND RECOMMENDATIONS

Despite its challenges, the development of RAS-BD technology able to track the health of ecosystems that underpin our very existence would be an enormous achievement. The majority of biodiversity experts foresee major benefits in using RAS-BD monitoring technology, but view it as an additional tool to supplement, not supplant, traditional methods. However, there are some doubts about the applicability of the technology to certain taxa, and concerns about negative effects, such as increasing the focus on some species to the detriment of others. Nevertheless, if RAS-BD technology could monitor just 10% of species at appropriate scales and time periods, it would be a significant improvement on current methods.

Many of the enabling technologies, fundamental tools and robotic capabilities needed for RAS-BD monitoring already exist in some form. Cutting edge research within the UK robotics community, albeit for other applications, has led to significant progress being made in developing potential solutions to the barriers that ecologists encounter. There is, however, a wide gap in understanding that separates RAS and biodiversity communities. Biodiversity experts tend to have a limited appreciation of advanced engineering technology and the technical challenges faced by RAS developers, while RAS experts often fail to understand the complexity of biodiversity itself, and the practical realities of monitoring it within real world environments outside of the laboratory. Fostering closer links between these two communities to bridge this gap and share ideas would overcome a key stumbling block in developing full-functional RAS-BD monitoring technology. In the words of one RAS workshop participant:

"There is a HUGE gap between lab and product. The main problem is going to be how to get economies of scale to enable rugged and tested units to be deployed".

To address these issues, while embracing the UK's wealth of RAS and biodiversity specialists, we make the following observations and recommendations:

- The UK has a vibrant community of experts working at the forefront of RAS developments for a diverse range of applications, but relatively little attention has been paid so far to using RAS to monitor environmental sustainability. Our exceptionally strong UK biodiversity research community plays a leading role in global ecological research. To advance the development of biodiversity-suited RAS technology, it would be beneficial if an integrated multidisciplinary task force, including academics and industry specialists with expertise in RAS and biodiversity, could be created and funded to achieve this goal.
- There are several areas where existing RAS capabilities, most of which have been developed for unrelated applications, are suited to monitoring biodiversity. Future UK funding and focus should be prioritised for those areas where these capabilities are aligned with biodiversity needs.
- Beyond the initial 'easy win' projects to develop and optimise first generation RAS-BD monitoring, lie many other nascent technologies. These technologies need increased and accelerated research and development funding to turn pioneering robotics concepts into enhanced RAS. This current research involves numerous UK academic teams working in new areas of technology that could lead to the next generation of RAS-BD systems suited to the hardest monitoring barriers that ecologists encounter.
- Education strategies should be developed to foster links between aspiring engineers, biologists and computer technologists, both in the curriculum of schools, and at a later stage in universities and research facilities.

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ANNEX: SELECTED BIBLIOGRAPHY

We list below a selection of relevant recent papers that were included in our literature review of methods used to monitor biodiversity.

Review Papers

These papers review the usage of camera traps, thermal imaging, passive acoustic monitors/recorders, UAVs, AI for automated identification, deep learning in ecology and RAS technologies to monitor biodiversity.

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Methods

A selection of papers that discuss traditional techniques, current developments, and advances in methods for monitoring biodiversity.

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> “Despite its challenges, the development of RAS-BD technology able to track the health of ecosystems that underpin our very existence would be an enormous achievement. The majority of biodiversity experts foresee major benefits in using RAS-BD monitoring technology, but view it as an additional tool to supplement, not supplant, traditional methods.”

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