Lloyd's Register Foundation

Foresight review of robotics and autonomous systems

Serving a safer world

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About the Lloyd's Register Foundation

Our vision

Our vision is to be known worldwide as a leading supporter of engineering-related research, training and education, which makes a real difference in improving the safety of the critical infrastructure on which modern society relies. In support of this, we promote scientific excellence and act as a catalyst working with others to achieve maximum impact.

The Lloyd's Register Foundation charitable mission

- To secure for the benefit of the community high technical standards of design, manufacture, construction, maintenance, operation and performance for the purpose of enhancing the safety of life and property at sea, on land and in the air.
- The advancement of public education including within the transportation industries and any other engineering and technological disciplines.

About the Lloyd's Register Foundation Report Series

The aim of this Report Series is to openly disseminate information about the work that is being supported by the Lloyd's Register Foundation. It is hoped that these reports will provide insights for the research community and also inform wider debate in society about the engineering safety-related challenges being investigated by the Foundation.

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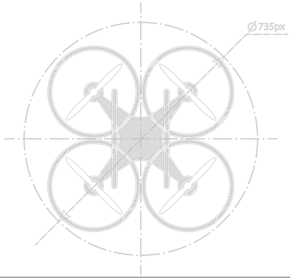

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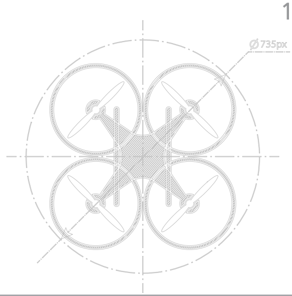


Executive summary

There is a revolution happening around us and all over the world. Smart, connected machines, or robotics and autonomous systems (RAS), are acting as tools to support us, working alongside us or alone, making independent decisions and even learning. They act and sense in the real world, connected and collaborating in the internet of things, generating and enabled by large quantities of data, using artificial intelligence to reason, classify, control and interact. They have emerged from research prototypes into practical applications.

Autonomous and semi-autonomous cars on our streets are one very public example. Other RAS include manufacturing systems that can personalise bespoke designs and reconfigure during normal operations; robotic fulfilment centres that assemble, package and dispatch goods ordered online; drones that deliver packages, or map, inspect and repair in our offshore oilfields and nuclear facilities; assistive exoskeletons to help us move and lift; and interactive companions for the elderly and isolated. In the same way the information and communications technology (ICT) revolution affected everything that uses data, the RAS revolution is changing everything that moves.

The drivers for this revolution are primarily economic – these systems make us more productive, mobile and connected, able to compete in a globalised world economy. However, they also remove operators from hazardous environments and tedious jobs, taking on the dull, dirty and dangerous tasks. There is therefore an important impact on the safety of people and of their environments. There is also an important need to build RAS systems safely, so they act dependably and appropriately in all situations, including when they fail. This review looks at RAS through this safety lens, and on the opportunities for improvement they present.

There are multiple ways RAS are being used to improve safety. As well as removing people from hazardous situations, they may be an integral part of a system in partial control such as an aircraft autopilot. As tools that physically collaborate with people, they can act as assistants to prevent injury, for example as a body exoskeleton during lifting. They can perform inspection of assets such as structures or pressure vessels more frequently, with greater access, more sensors and less down time than people, leading to earlier defect detection and greater reliability. They can operate in environments where humans cannot go, for example undersea mining and drilling or entering collapsed buildings. Finally they can be used in safety critical situations to detect and reduce errors, for example in robotic surgery tracking adjacency to obscured critical blood vessels and providing warnings through an appropriate interface.

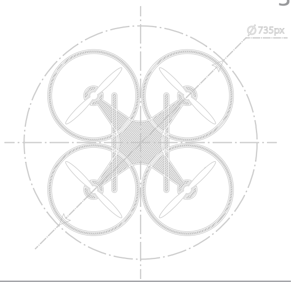
RAS can have an enhancing role in the safety certification and assurance of assets. However, they themselves must be similarly certified and assured, or they will become the limiting assurance factor of the complete system. The way they generate and have their actions driven by data is at the heart of their utility bringing issues and opportunities in data curation, sharing, ownership, aggregation and standards. A potentially disruptive development is in systems with embedded RAS that can self-certify to some assurance level during operation, impacting safety but also insurance and assurance business models.

Many RAS operate in environments that are unstructured and unpredictable to some level. Designing predictable safety into the behavior of RAS where unknown events can take place requires a different approach. The way RAS can learn presents further assurance challenges. Beyond recording events, RAS may infer derived knowledge such as predicting the behaviour of others. Learning may also extend to the underlying logic of the decision making process on how the RAS should act next. In both cases, this learning should be assured to be correct by some means and to some level of acceptable risk.

Linked to this is the nature of the RAS interaction with the human operator and where decision responsibility lies. Operators make poor decisions when a RAS unexpectedly hands over control, unless they have maintained a thorough situational awareness. Operators with poor situational awareness who do not trust a RAS may override it leading to catastrophic failure.

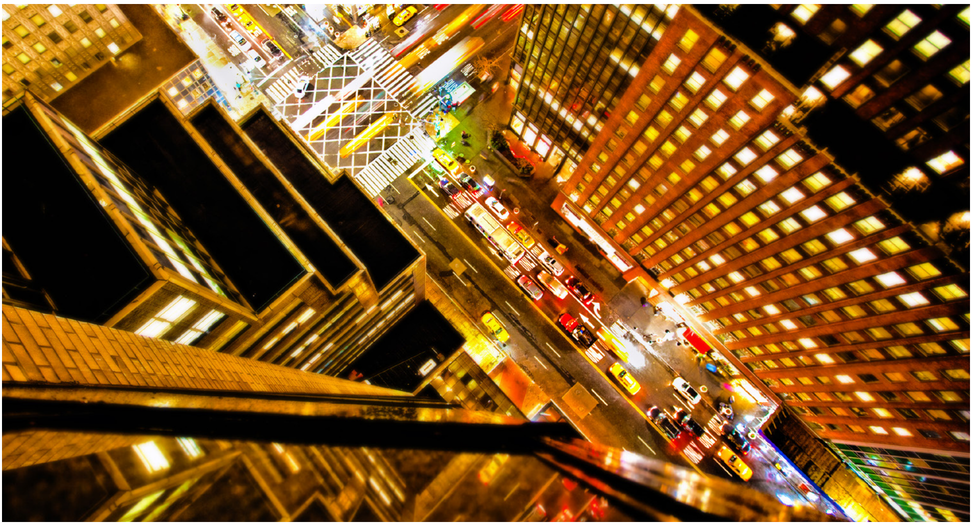
Safe operation of connected RAS requires they cannot be accessed illicitly. Embedding cybersecurity into RAS is a topic in its infancy, alongside use of distributed ledger methods for guaranteed records of RAS transactions. Similarly, safe and correct decision making is based on a code of human, ethical and moral factors – should RAS be allowed to practice deception, or override a human? For RAS to behave appropriately these have to be captured and condensed into guidelines that are coded in to the RAS design. Monitoring and developing these ethical guidelines as RAS capabilities evolve is an important activity.

The public must trust their RAS if they are to be adopted. Apart from observing them reliably performing tasks always, this also requires public support and contribution in developing the ethical frameworks that underpin RAS behaviour. People already anthropomorphise their robots, indicating public trust is possible. Fears about the nature of disruption in the jobs market should also be addressed. RAS will be deliberately designed as assistants rather than replacements for people, freeing professionals to spend time on creative and human-facing tasks. Skills development starts with supporting teachers in schools with STEM resources, the training of RAS technicians, engineers and scientists, development of business skills to create value that increases safety in disrupting markets, and up-skilling for those no longer doing the dull, dirty and dangerous tasks.



Living laboratories in existing infrastructure can have a key role to play. Capability based demonstrations in realistic environments provide a sharp focus to aim developments from basic RAS scientific research into first prototype demonstrators. Thereafter the same living laboratories provide the playground where commercial prototypes are de-risked and certified though long hours of operation and modification in the spiral of requirements and technology development.

This report finishes by recommending areas of further work that will help ensure the safety benefits from RAS are realised. These include issues of: openness and sharing; assurance and certification; security and resilience; and of public trust, understanding and skills.



Many RAS operate in environments that are unstructured and unpredictable to some level.

Foreword

People have always been fascinated with the idea of automated assistants. In the 4th century BC, the Greek mathematician Archytas of Tarentum postulated a mechanical steam-operated bird he called 'The Pigeon'. In Renaissance Italy, Leonardo da Vinci sketched plans for a humanoid robot. Remotely operated vehicles were demonstrated in the late 19th century in the form of remotely controlled torpedoes. The first use of the word 'robot' however was in the Czech writer Karel Čapek's 1920 play Rossum's Universal Robots. It featured artificial people called roboti (derived from 'rab' meaning slave), who could think for themselves.

Since then robots have been a strong presence in science fiction and popular culture, often accompanied by a narrative of the potential dangers of increasingly intelligent artificial systems. This has fuelled public concern about safety, job security and the ethics of decision making by automata. In parallel, engineers and scientists have been reaping the benefits of the increasing computational capacity of computers. They are building robotic systems ever more adaptable and capable, using new machine learning and artificial intelligence techniques. Industrialists meanwhile have recognised this new generation of smart machines can increase productivity with flexibility, thus helping to expand international market share and secure business.

Numerous communities including engineers, scientists, industrialists, researchers, research funders, venture capitalists, ethicists, economists, lawyers, public policy makers, insurers, regulators and standards bodies are now engaged in thinking about the application, opportunities and issues with robotics.

This review looks at robotics and autonomous systems (RAS) through the lens of Lloyd's Register Foundation. The Foundation commissioned it to identify the safety opportunities from RAS and to explore if there are 'white spaces' where the Foundation can focus support to make a difference, seeking to secure high technical standards to enhance the safety of life and property. To this end an international group of experts from a range of stakeholder perspectives assembled for a workshop in London in March 2016 to consider this new way of thinking about RAS. An online consultation was also opened with respondents contributing from all over the globe. This review sets out the findings of these discussions, examining the issues from a wide range of perspectives. It shows how RAS are already being used to enhance safety and how these capabilities might grow. Its findings shine a light on the positive contribution robots will make to society, and makes the case for robots that serve a safer world.

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An autonomous underwater vehicle inspecting underwater oil and gas equipment. RAS are already being used to enhance safety and these capabilities might grow.

Background

This review shines a light on the positive contribution robots will make to society, and makes the case for robots that serve a safer world

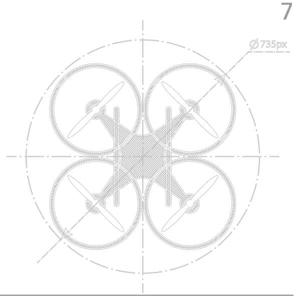
This report is the fifth in a series commissioned by Lloyd's Register Foundation as part of its emerging technologies research theme. It looks forward at how developments in the area of robotics and autonomous systems (RAS) might impact the safety and performance of the engineered assets and the infrastructures on which modern society relies.

Lloyd's Register Foundation is a charity and owner of Lloyd's Register Group Limited (LR). LR is a 256 year old organisation providing independent assurance and expert advice to companies operating high-risk, capitally intensive assets primarily in the energy, maritime and transportation sectors. It also serves a wide range of sectors with distributed assets and complex supply chains such as the food, healthcare, automotive and manufacturing sectors.

Building on the findings of this review, the Foundation will look to identify aspects of robotics and autonomous systems that might provide opportunities or threats to safety in line with its charitable objectives, and where the Foundation might focus its research and other grant giving to make a distinctive positive impact.

The Foundation is a charity with a global role. Reflecting this a core group of principal authors met in January of 2016 to consider the structure and format of the review. From this an international expert advisory panel comprising technical, ethical, legal, economic, societal, commercial and government interests were identified. They assembled in London in March 2016 for a two day workshop to consider the review from these various perspectives. In parallel an online consultation was made generally available, and comments also received. This report contains the output and findings from the panel and the consultation.

Expert panel membership



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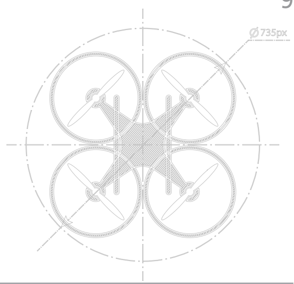
Introduction to robotics and autonomous systems



Beyond automation and control, robotics and autonomous systems (RAS) are interconnected, interactive, cognitive and physical tools, able to variously perceive their environments, reason about events, make or revise plans and control their actions. They are assistants that work alongside us to perform useful tasks with and for us in the real world, extending our capabilities, reducing our risks and increasing our productivity. RAS may be thought of as the eyes, arms and legs of big data, perceiving, making decisions and taking action. When interconnected, for example within the 'internet of things', the physical impact of RAS can be enormous. Autonomous systems do not necessarily have to create a 'physical' action via a robot. They can also make decisions and act within digital systems for example in financial exchanges.

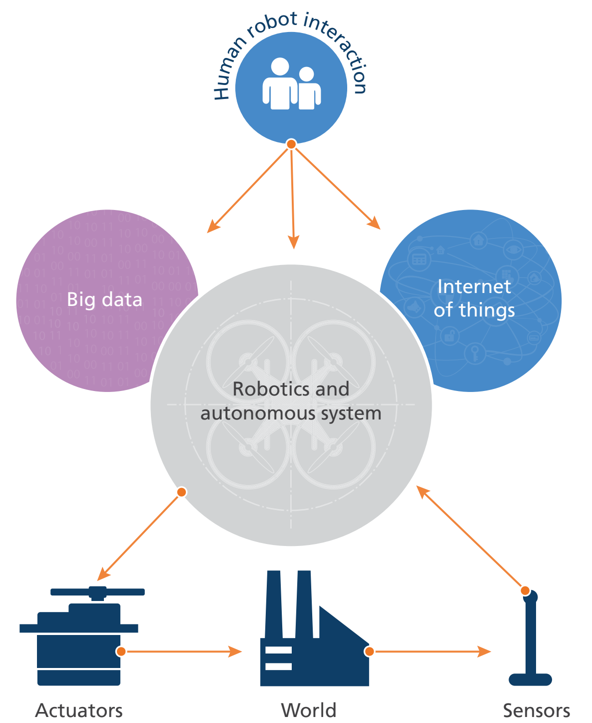
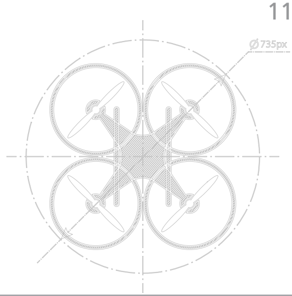


Fig 1: RAS are the arms legs and sensors of big data working in the internet of things

A worldwide revolution is happening in the development and application of these systems in all sectors. In the same way that the information and communication technology revolution affected everything that uses data, the RAS revolution is affecting everything that moves. It is happening now for two reasons. First, powerful processing is available in small and low cost forms and software implementing advanced data processing and machine learning is making robot hardware more capable. This endows the robot with the ability to sense and build descriptions of its local environment, plan and re-plan its actions, control its appendages through motion and contact, navigate and communicate, often using artificial intelligence (AI) technologies. Second, these RAS make people and companies more productive, providing a compelling commercial incentive to adopt and compete. These systems also reduce risk to people, assisting us by doing dull, dirty and dangerous tasks.

RAS interact. They interact physically with their environments, with each other, with people and with themselves to monitor self-performance. Some are persistently autonomous operating for extended lengths of time in environments where it has limited or no knowledge, self-adapting purpose in response to unexpected events and disturbances and recovering from errors in task execution. Others use shared autonomy, working closely with an operator, planning and controlling collaboratively with the human, offloading part of a task execution, but with the operator fully engaged and situated with events.



Glossary

Robot: Robots are physical machines, that perceive, move and engage with physical things with purpose. They embody autonomy-enabling abstract data processing and decision making to act on the physical world.

Autonomous systems: Autonomous systems make decisions. They use data, information and knowledge to inform decision making. They can be distributed or localised, they can seek information from many sources, including the internet, or just use the data available locally. Autonomous systems are outward looking, they sense, impact and interpret the real world making decisions as their external environment changes.

Automatic systems: Familiar automatic systems include dishwashers, car washes, and anti-lock braking systems. Automatic systems do not interpret, infer, reason or use cognition. Their sensors are precisely placed to deliver the exact data needed to move to the next part of a pre-determined cycle; water level, temperature, flow, wheel speed, all detected with single point sensors carefully designed to exactly deliver a guaranteed result. Automatic systems are often inward, only sensing pre-defined quantities in a finite space, such as a washing machine.

Artificial intelligence (AI): AI is a sub-field of computer science that develops computational techniques typically implemented in software to solve the general problem of simulating (or creating) intelligence. The central topics tackled by AI include reasoning, knowledge representation, planning, learning, natural language processing (communication), perception and the ability to move and manipulate objects. A currently active branch of AI is machine learning. Here, highly parallel computational structures, loosely modelled on simplifications of the neuronal structures of the brain, have internal gain settings tuned (or trained) by being shown large quantities of data that has been labelled to identify what class it is. They are subsequently used on unseen data to classify according to these labels.

Drones: A drone is an unmanned aerial vehicle (UAV), or unmanned aircraft system (UAS). It can operate with various degrees of autonomy: either under remote control by a human operator, or fully or intermittently autonomously using onboard computers. Latterly the term has also been applied to other forms of unmanned system including unmanned underwater vehicles (UUVs).

There are broad classes of capability that are demonstrating RAS[1].

- Data gathering: RAS are used to observe and inspect a process, infrastructure or system, assess performance, identify failures or features, or simply provide status data. These monitoring operations can be carried out on infrastructure, industrial plant, buildings, vessels, civil infrastructure (bridges, roads, harbours), people, farms or animals.

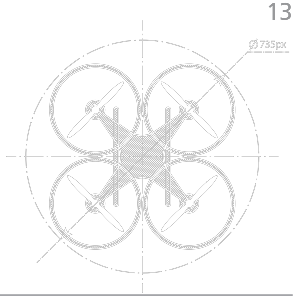
- Transportation: RAS are used to convey items over short distances, such as inside a factory, or long distances on roads, at sea or in the air. The RAS must know where it is, where it can go and where it needs to go. It may be transporting goods or people.

- Manipulation: RAS interact with objects and materials. They recognise, select, grasp and manipulate raw materials, objects and parts. They can assemble or disassemble them, interacting with flexible materials and soft objects, bending, shaping, fitting, cutting, polishing, grinding, drilling holes or cleaning.

- Sorting and storage: RAS are used to sort, pack, unpack and store goods, raw materials and parts. The system is responsible for the correct identification of parts and of keeping track of where each item is in the system. The items being sorted and stored might be packages in a delivery chain, parts in a warehouse, blood samples in a hospital, or fruit in boxes in the back of a van.

These capabilities are being applied across a range of sectors. For extreme and hazardous environments such as offshore energy, new generations of autonomous underwater survey and inspection vehicles are in routine commercial use. New generations of hover-capable intervention vehicles that can dock and perform simple manipulation have been demonstrated in research laboratories and are ready to transition to application. In infrastructure markets aerial drones are routinely mapping assets (for example, buildings, oil rigs, railways). In transport, self-driving and driver-assist cars are a focus of car companies and governments following capability demonstrations in the DARPA Grand Challenges and subsequent interest from Google. Similar developments in rail and shipping are underway. In health, social care and domestic applications, robot companions and assistants are already on the market, as are bionic prosthetics. Surgical robots are commonplace. In manufacturing, new robots that can work co-located and in co-operation with an operator are now available. These are being used

[1] https://connect.innovateuk.org/documents/2903012/19163277/The%20UK%20Landscape%20for%20Robotics%20%26%20Autonomous%20Systems



for bespoke but mass manufacturing to customer order. In warehousing, robotic systems are moving goods ready for shipment. In the future we can expect these shipments to make use of drone delivery.

Governments and companies around the world are investing heavily in research and innovation in this space. The EU H2020 programme is investing 700 million euros[2]. Following release of the RAS2020 strategy in 2014[3], the UK government has invested over £200 million in five Centres for Doctoral Training[4], capital equipment, innovation projects and in the Centre for Connected and Autonomous Vehicles[5]. In Japan, the Robot Revolution Realization Council has initiated a similar scale of investment in Japanese industry and research institutes[6]. Both China and Korea are making major investments, and the US with major programs in DARPA, National Science Foundation, the Office for Naval Research and other public agencies.

The largest impact to date of RAS has been on manufacturing, continuing in such initiatives as Industrie 4.0[7] and the European Commission's Digitisation of European Industry strategy[8]. Other markets for RAS have opened up in surgery, home appliances, hazardous environments and is starting to impact on transport. However there are other applications where RAS can have great impact in the delivery of professional services and in the operation, inspection, repair and maintenance of infrastructure. Some of these require a step change in thinking about the use of RAS where safety and assurance provide the key rationale. This report identifies the challenge this poses and marks out the opportunity exploring the developments that might be taken to enable RAS as assistants in the service of a safer world.

[2] http://ec.europa.eu/programmes/horizon2020/en/h2020-section/robotics
[3] https://connect.innovateuk.org/documents/2903012/16074728/RAS%20UK%20Strategy?version=1.0
[4] http://hamlyn.doc.ic.ac.uk/uk-ras/
[5] https://www.gov.uk/government/collections/driverless-vehicles-connected-and-autonomous-technologies
[6] http://www.meti.go.jp/english/press/2015/pdf/0123_01b.pdf
[7] https://en.wikipedia.org/wiki/Industry_4.0
[8] https://ec.europa.eu/digital-single-market/en/digitising-european-industry

Applying robotics and autonomous systems to improve safety

People want to live and work in a safe environment but many human activities carry risk that frequently derives from human decision making. Most often human factors (for example, limited perception, cognitive bias, tiredness) can impair human decision making, but not that of RAS. Technical factors, such as the ability to compute from large collections of data, can also make RAS more capable and more predictable. However, ethical and moral choices which are straightforward for humans are currently difficult to encode into a machine. The real benefit and performance comes from humans and machines interacting and collaborating making the best of human and machine skills in combination. For example, one of the primary reasons for developing autonomous road vehicles is the reduction in accidents that would result from autonomous operation.

People are prone to making basic errors of judgment, for example when they are tired, or driving a long distance at speed and suddenly encounter changed conditions such as fog, rain or slow traffic. The programmed behaviours of an autonomous car can be developed to react consistently and in a timely and responsive manner to such changes, thus using the repetitive reliability of machine-based decision making to counter the unreliable and variable decision making of a human driver. On the other hand a human driver may have to decide how to minimise the effect of a collision and that may rely on an individual's moral subjectivity that is difficult to code into an autonomous vehicle.

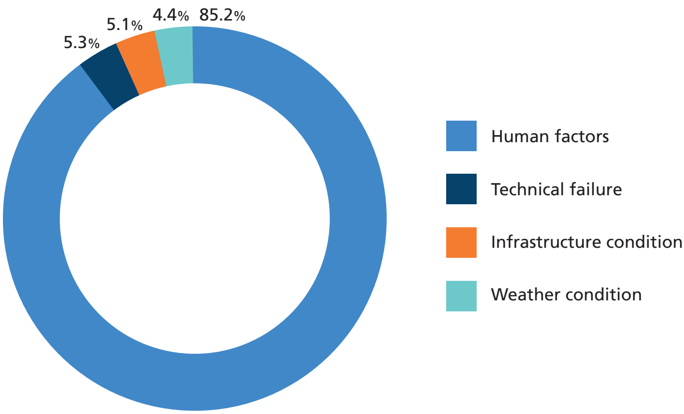
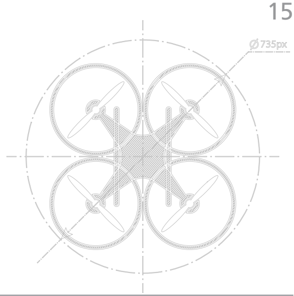


Fig 2: Main causes of truck accidents, European Truck Accident Causation (ETAC) study, The International Road Transport Union (2007)



This section identifies a number of scenarios that illustrate how RAS can enhance safety, applicable across different sectors and areas of application.

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Removing workers from harm

The first and most common in current use is where a robot is used in place of a person to carry out a hazardous task with an operator controlling the robot remotely from a safe location. In this type of application it is highly likely that the person does not fully control the robot in every aspect of its operation in the way that a crane operator controls each axis of motion. Instead the robot makes local decisions that keep it operating, for example hovering at a fixed position, and the user directs the task. The limited autonomy exhibited by the robot is sufficient to make the remote operation viable and more efficient.

For example in the 1970s all North Sea oil platforms and infrastructure were maintained by saturation divers, highly trained and well paid, but exposed to significant risk through prolonged periods under pressure. By the 1990s, less than 20 years later these divers had been largely replaced by remotely operated vehicles (ROVs) tele-operated by pilots using umbilical cables from vessels. As part of the heightened safety culture of the North Sea, these ROVs reduced the death and injury rates. This trend is continuing during the 2010s with the introduction of the first commercial autonomous underwater vehicles for inspection. Research is underway so that soon these will also be able to carry out light intervention tasks autonomously, for example, turning valves, cleaning, and lifting.

RAS in partial control

The second main category of RAS that improves safety is where RAS constitutes an integral part of the operation of a system such as aircraft autopilots. They algorithmically replicate instrument flying and every day millions of passengers travel more safely as a result. In this scenario RAS takes full control of part of a process or task thereby reducing the load on a human operator.

Another example is in mining where there is increasing use of autonomy to both remove workers from dangerous environments and reduce the number of people working underground. Fully automated transport systems are already being used in some mines. A scoop is operated by a person to collect material but control is then handed back to a RAS to navigate through the passages in the mine to the delivery point. As a result people are completely excluded from this area of the mine. The operator is simply an observer during the truck transit and can therefore have oversight of a number of vehicles. The mine infrastructure has been altered to make the integration of RAS highly effective. There are good indications that in the future a number of mining operations will be automated through RAS technology, not through remote operation but through shared autonomy. As a result operators would be removed to the surface. Mines that integrate RAS in this way can also become more efficient because transit speeds are increased when no humans are present.

In the future RAS will form an integral part of complex systems and plant whose operation would not be otherwise possible. Take for example the proposed ITER fusion reactor in which key components of the reactor, that are comparable with the fuelling systems in a fission reactor, will be exchanged remotely. More generally, routine inspection and maintenance will be conducted using drones and mobile vehicles equipped with snake-like arms. This minimises installed equipment which would degrade over time due to radiation.

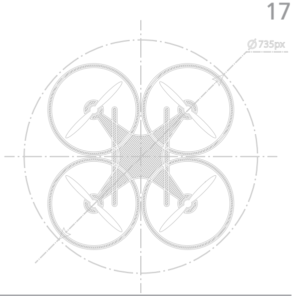
Active collaboration with people

The third category concerns the use of RAS that provide safety as a direct outcome of their operation. Here RAS is used as a physically collaborative system, either in the workplace or in the home; it is designed to provide safety as an active part of its function rather than a side effect of its operation. For example RAS can be used to provide physical support for a person protecting them from harm. They can also reduce strain injuries by collaboratively supporting a workpiece or tool during a repetitive task.

RAS may also be able to actively prevent falls or stepping into danger. Such systems are of value in the work place to reduce accidents and in the home to protect the frail and elderly. Driverless vehicles also fulfil this function by assisting those unable to drive to remain safely mobile.

Inspection of assets and infrastructure

The fourth category of safety enhancement with RAS ensures safety through offline inspection. Major safety critical assets need to be regularly inspected, for example pressure vessels in the oil and gas industry. With human-based inspection such vessels have to be physically disconnected from the plant; turning off control valves alone is insufficiently safe. The vessel



must be vented until the vapour level is safe enough for a suitably protected person to enter, who must then clean, inspect and if necessary repair the vessel before it can be sealed, tested and reconnected. All of this has a plant cost in lost operation, made longer and more expensive by the strict safety criteria necessary for human-based inspection. Carrying out such an operation using RAS would reduce the operational safety requirements and speed up the process thereby reducing costs and at the same time providing a more thorough inspection.

Other examples of improving safety through RAS-assisted inspection include the external and internal inspection of ship hulls and aerial inspection of infrastructure using drones. RAS provides enhanced safety by reducing the risks for human operators and providing repeatable inspection of the asset.

Operating in ‘no-go’ environments

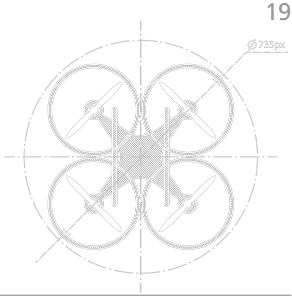
The fifth and related example of RAS impacting on safety is in performing tasks where it is impossible for a human to go or where the risk is unacceptable. For example entering a collapsed buildings after an earthquake or explosion, extracting mineral resources in dangerous conditions, such as in undersea mining operations, in mines where the risk of roof collapse is too high, or in maintaining nuclear reactors. In these environments RAS will be the only way that tasks can be carried out.

RAS assuring safety critical operation

The final example of RAS enhancing safety is where RAS is used in safety critical processes to reduce and spot error, or potential error. For example in surgery where the surgeon is in full control of his instruments RAS augments each instrument with warning indicators providing feedback, based on a real time model of the patient, indicating, for example, where critical blood vessels lie out of sight. Here the RAS is used to 'understand' the operating environment allowing the operator to concentrate on the task at hand and relying on the RAS to assist in reducing errors. RAS can also be used in the quality control of high throughput routine tasks, reducing human error by detecting and correcting defects for example in the manufacture of safety-critical machine components.

Beyond the above there will be future applications of RAS that will bring unforseen safety benefits in our rapidly changing world. The potential safety benefits from RAS are multiple and profound. However they will not be realised unless some fundamental issues are acknowledged and addressed. The following sections address some of these issues, including safety assurance and design; public awareness and trust; the human skills needed to implement RAS, and the commercial considerations for investment.

Assuring assets with robotics and autonomous systems



Asset assurance using RAS

Assurance of assets to certify operations are safe for both people and the environment is an essential task in most industries. It takes place as part of the system design, but also as part of build and commissioning, and subsequently at periodic intervals during operations. It involves both making measurements and using models to estimate condition and therefore likelihood of a failure and the resulting consequences. 'Assets' refers to both the digital and physical entities that form a system.

RAS offer safety-enhancing as well as cost-reducing capabilities in asset certification and assurance and in overall integrity management and maintenance. These come partly from the feasibility and reduced risks and costs of deploying robot(s) to make measurements (for example, in hard to reach places), but principally from the increased frequency and accuracy of opportunistic and scheduled observation and maintenance of the asset. This leads to early awareness of incipient problems and ultimately reduced asset downtime for maintenance or repair. It may also lead to new ways of carrying out certification not previously possible.

RAS offer safety-enhancing as well as cost-reducing capabilities in asset certification and assurance and in overall integrity management and maintenance

A RAS information architecture that makes available knowledge services so that RAS can access maintenance data, procedures and update itself with mission plans, brings into play the notion of a smart space. Within such a service oriented architecture, generic RAS hardware can be adapted for different kinds of missions. Here the infrastructure is also smart and can store and collect data to assist the RAS on arrival.

However, RAS introduced into the assurance and maintenance of safety critical or very high value systems must have their own operation assured. They must deliver the required performance and reliability, otherwise they become the limiting assurance factor for the complete asset.

The role of data

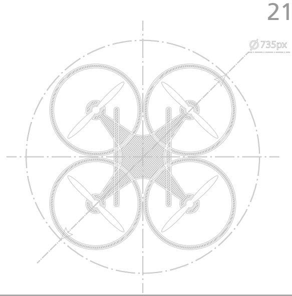
Obtaining lots of data requires instrumentation which may be expensive and itself can be a cause of failure. Traditional assurance has therefore often reverted to inspection by a person to improve reliability and reduce costs. Using RAS instead enables new data to be collected, archived and used as well as removing people from potential hazards.

Aggregating and interpreting data

RAS gather data while operating. RAS use sensors to detect and probe the environment, moment to moment, to decide how to move and how to proceed. This data comes from a diverse range of sources and from the robot's own sensors, and may include precise information about location as well as data from other RAS, remote sensors and the internet. To make decisions RAS integrates and interprets these diverse data sources in order to combine both 'where' and 'what' information. RAS dedicated to inspection will also aggregate data from dedicated sensors, for example to detect cracks in aircraft structures, or pipe walls, or measure the chemical contamination in a harbour.

Robots learn about their specific local environments. But they also share knowledge with other robots in other locations drawing on experiences across classes of assets. They can also make decisions on wider knowledge for example about prediction and failure based on learning from corrosion patterns in steel structures and then applying this knowledge within their asset class and specific local environment. This process of aggregating and interpreting data derived from multiple sources adds value to that data. Part of this added value enhances safety first by removing human factors from the inspection task itself, as more systematic and thorough inspection can be carried out, particularly when multi-modal data is aggregated against precise location. Second this data can contribute to a long term data bank that can be used to compare the asset from one inspection to the next providing the ability to track and trace the development of faults. For example, an area being inspected may not immediately show the known prior markers of a defect and then a failure occurs. By examining a comprehensive set of accumulated data that pre-dates the failure a better understanding of prior markers can be obtained.

In human inspection this data would not be collected, however in a RAS based inspection all data can be collected and compared. This extension of the inspection task has the potential to add to the safety of the complete inspected asset class through the aggregation of data from multiple examples of a single asset. Analysis of this data may then be used to alert other asset owners to carry out pre-emptive inspections or alter existing inspection regimes thereby reducing failures and increasing safety.



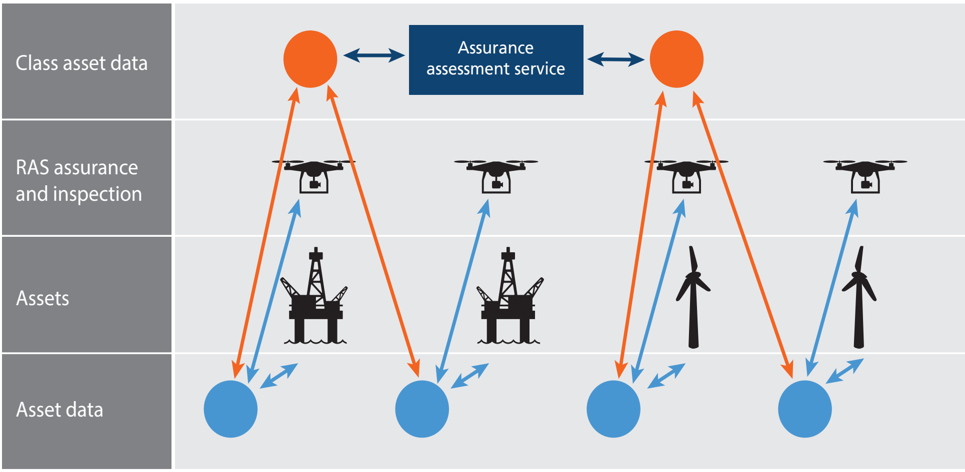


Fig 3: Asset-to-asset and asset class data storage and analysis

This centralised data may need to be curated automatically so that value can be derived from identifying new events, for example a new type of failure, or from progressive change over time highlighted within a historical analysis of the data stream. If such a database can be constructed the accumulated knowledge base becomes both part of the infrastructure of the asset, but also an infrastructure in its own right because the data has value beyond the asset it was collected from.

Ownership of data

A key issue is who holds and has access to data (including any personal privacy issues), for example the digital model of the asset and the survey data providing integrity information such as cracks. Typically this is sensitive information the asset owner may be reluctant to share. However, sharing is a key requirement to enhance safety, efficacy of machine learning and to encourage bidding competition amongst contractors. Open data standards and initiatives help this and are being championed by governments for greater transparency. First steps can be to form data sharing clubs to open the boundaries of privacy.

Establishing the right commercial model for data gathering improves safety. Asset lease arrangements by manufacturers and power-by-the-hour[9] charging have motivated data gathering for big data analytics, achieving high reliability and rapid in-situ maintenance from a well-informed integrity and maintenance service. This model suits the deployment of RAS as part of the service.

Standardisation of data

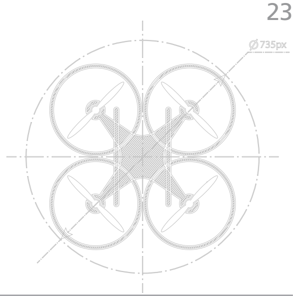
The collection, curation, storage and analysis of asset data will require standards and a metrology that cut across sensors, assets, asset classes and organisations, and will need to consider the security and corruptibility of data at any point in the data lifecycle. Such standards will have to be global since the impact of this level of data aggregation will affect inspection and maintenance tasks across multiple sectors and types of installation. Achieving such interchange may need an independent body able to define data formats and classes and develop standards in collaboration with supply chains. That there may be strong parallels here with the development of Building Information Modelling (BIM) used in the construction industry with the potential for best practice transfer from that industry.

Self-certification and assurance

Inspection for certification is often labour intensive, risky and expensive. It is usually performed periodically at pre-determined times according to statistical criteria. The certification process may be very linear, relying on work flows and tick boxes. RAS technology can enable assets to self-certify in a more agile way during normal operation. Not all aspects of current certification requirements might be met, but increase in RAS uptake will drive a change in certification practice and standards. There will be an increased move towards probabilistic assurance against the occurrence of critical events.

If accepted by regulatory bodies, such a capability will be a disruptive influence. As well as reducing risk to people and infrastructure it will change business models and add value for asset owners and operators and for the assurance industry. Continuous self-assurance from remote locations could become part of a standard remote operation suite, through locally embedded RAS for integrity management, inspection and intervention for maintenance.
An additional assurance need arises where the RAS employs self-learning. If the RAS learns falsely it can undermine the asset's built-in integrity. The opportunity to curate knowledge and data over time about safety will be lost. In this way self-learning RAS will need an additional assurance mechanism.

[9] For example http://en.wikipedia.org/wiki/Power_by_the_Hour



Life extensions of assets are increasingly common and may present a cost effective opportunity for early adoption of self-certification approaches, increasing asset integrity and safety and reducing operational cost. Early adoption can also be stimulated by financial and legal instruments such as capital borrowing costs, credit ratings, insurance costs, regulatory actions and the development of codes and standards.

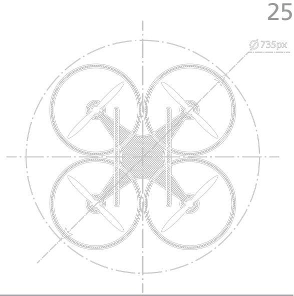
Software systems integrity management

Smart software is at the heart of the new generation of RAS. Industry standard methods for designing and assuring safety critical code to software integrity levels (SIL) exist. Through these RAS software can be assured from the outset through design methodology and approach, however higher assurance comes at a cost. It requires quality processes at design and build time, and this will be a key factor in determining the adoption of RAS. High levels of guaranteed internal software integrity may make the RAS uneconomic and unattractive.

There are methods to reduce the software assurance demand such as embedding fault detection and diagnosis on the RAS. In the event of failure, continued but degraded operation may still be desirable according to cost and safety criteria.

The new industry of digital forensics used in financial services and digital currency offers a relevant complementary capability. Distributed ledgers offer a guaranteed transactional history of events. This technology may be used to improve the assurance level of RAS recording and sharing events as a basis for planning or re-planning actions.

RAS software systems connected to the internet are vulnerable – cybersecurity is a key issue in protecting against malicious attack by viruses and other means. Only through greater cross fertilisation between the RAS and cybersecurity research-and-innovation communities can the required software integrity levels be achieved. This will also need to extend to assurance levels for software used from third party resources.



Key points

- RAS can enhance safety and reduce costs in assurance. For legacy systems RAS assurance comes from stand-alone systems. However increasingly new infrastructure designs will build in RAS as an integral part of operation, control and assurance. Many RAS will be self-learning drawing knowledge from individual assets but also from experiences across a class of assets and types of fault. Therefore the assurance of the RAS itself may limit the degree of assurance if it does not meet the same levels of assurance as the asset.

- The knowledge from multiple sources of data applied at a precise location adds value.

- Sharing data improves integrity, saves lives and encourages contractor competition. Open data standards make this technically feasible. Clubs help to avoid sensitivity and privacy issues.

- The data history of assets can be more comprehensive allowing the long-term analysis of failures and asset performance. Once curated it becomes an integral part of the asset.

- Establishing the right commercial model for data gathering and maintenance improves safety and will be needed to facilitate uptake of RAS.

- Global standards of data capture, curation and methodology are needed to reap the full benefit.

- Self-certification under operational conditions using embedded RAS on a remote asset will improve safety and change assurance industry business models.

- Assurance approaches to RAS that learn have still to be developed.

- Digital forensics, distributed ledger and cybersecurity methods are important for safety, alongside RAS software integrity levels.

Designing safe robotics and autonomy into systems

Safety starts with the design process and the design process starts with an analysis of function. Designing a safe system is easier when the interaction between the system and its operating environment is constrained and well defined. For example where a robot repetitively welds car body parts together on a production line, the operators can be protected from hazards through the use of interlocks and protective barriers. The machine and its working space are bounded and can be isolated from people to deliver safe operation. While this is not completely fool proof it provides a level of safety that can be tested and assured.

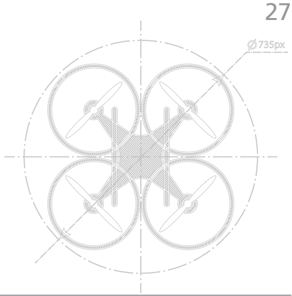
Safety starts with the design process and the design process starts with an analysis of function

Designing for uncertainty

With RAS that operate in our everyday environment, which is unstructured, complex and unpredictable, a different approach is required especially when RAS decision making has a safety critical element. This makes it harder to develop design and certification processes that will create and assure a safe system.

In an unstructured and unpredictable environment it is, by definition, not possible to identify all of the critical conditions that a robot may encounter. It may be difficult to determine which conditions are critical and even harder to replicate them for repetitive testing during development. For example testing collision avoidance with people in an autonomous vehicle. In addition it is important that the system itself is designed to be able to determine that it is operating within safe bounds, particularly if it is interacting with people or critical assets.

While basic safety can be designed into any product, for example ensuring that the product is unlikely to catch fire in normal use, designing guaranteed safety-critical decision making in an unstructured environment is challenging. Therefore the design of a RAS that must make critical decisions and impacts on the safety of people, requires processes and methods that are developed to ensure that the system is both designed and built to operate safely.



Designing for safety

To design for safety the design process should consider the RAS and the range and nature of interactions with its operators and users, taking into account that these may be skilled, or increasingly semi- or un-skilled, since the RAS is providing the skill uplift. Where skill has shifted to the RAS, the responsibility for ensuring safe operation is also shifted to the RAS.

Decision making will often be shared between the operator and the RAS device. This sharing can take place in a number of different ways, over different time scales and can be viewed as a spectrum of interaction.

User interaction and its limitations

At one extreme the machine may simply present the user with different overall goals to achieve and then largely be left alone (persistent autonomy). The user is removed from the task, placing the emphasis for performing safely on the RAS. Or the machine may present courses of action to select or require the user to direct the flow of high level tasks (shared autonomy).

At the other extreme the operator is directing the action of the RAS moment to moment while the RAS maintains stability and perhaps safety - a form of advanced tele-operation. The user will be required to concentrate on the task at hand in some detail, and is more able to identify and correct unsafe operation. This may also be the primary purpose of having the person in the control loop.

User interaction from tele-operation to persistent autonomy

For RAS working in unstructured environments there may come a point where the RAS cannot make a decision, or is perceived as making the wrong decision by the human operator. This potentially leads to a succession of failures. Where RAS is unable to make a decision there is currently an expectation that the operator will have to 'take over' the controls to ensure safe behaviour. The success of such a take-over will be impacted by several factors:

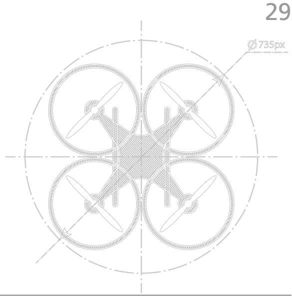
- The information step that the user has to absorb before making the next critical decision
- The time to the critical point where a decision has to be made
- The training or skill of the user in making critical decisions
- The attention level of the operator prior to the critical event.

For example an autonomous vehicle may suddenly encounter driving conditions such as smoke, fog or driving rain, where it can no longer provide safe interpretation of the environment that can inform its decision making process. If a human driver is alert then they may be able to successfully take over control, but it is likely that if the system has been driving itself for some time the driver will not be able to react in time, or react correctly, because of information overload. There are numerous examples of human information overload leading to poor decision making; Three Mile Island, the Air France plane crash in the Atlantic in 2009[10] and many others. In many of these cases it was the design of the user interface and the way that control was handed over that forced errors to occur when a human was suddenly reinserted into the control loop.

There are clear limits on the ability of humans to 'jump' into a critical situation and make the right decisions. In fact there is evidence that they may be more likely to misinterpret the circumstances and compound an already critical circumstance making failure more likely. This places fundamental limits on what people can be expected to do 'right', even with full training. It is therefore important to address the myth that human operators, even skilled ones, can be suddenly asked to 'take control' because the evidence is that they cannot do so safely[11]. This leads to the conclusion that it may be better to have a RAS continue to make decisions (including 'a considered or graceful pause') even if these result in failure because the overall probability of success is higher. In the future this circumstance will become more likely as the sophistication of RAS decision making increases. As RAS operate without human decisions for longer the circumstances where RAS cannot act will become more complex and thus humans will be even less able to take control. Design processes for RAS that make critical decisions therefore need to concentrate on failing well and managing information flows rather than only making perfect decisions and handing control to an operator when some decision threshold is reached.

[10] http://www.vanityfair.com/news/business/2014/10/air-france-flight-447-crash

[11] http://www.airbus.com/fileadmin/media_gallery/files/safety_library_items/AirbusSafetyLib_-FLT_OPS-HUM_PER-SEQ06.pdf



These limitations on human decision making will also limit the application of RAS. There will be applications where it is impossible to fully guarantee safety, thereby setting fundamental limits on what machine-based decision making can be expected to handle. In using RAS to enhance safety there will be a limit to the level of safety that can be achieved.

The design of systems that can communicate and collaborate, both with other RAS and humans in decision making will reduce the need to 'jump' humans back into the loop. With the objective that at critical moments where neither machine or human are able to make perfect decisions there is at least an optimised flow of information that might maximise the chances of good decisions being made, and the possibility that collective decision making between RAS may provide greater levels of safety overall. Such an approach will be relevant to the safety of every autonomous car.

Design for data privacy and standards for knowledge exchange

The design of safety in RAS is not limited to considerations of physical safety. Safety by design extends to the safety of data and data exchange that is necessary for RAS operation.

As has been explored above, all RAS gather data from their environment in order to function. At a basic level the data gathered from the environment must be stored and processed securely to ensure that there is no possibility of inappropriate third party access to that data. Indeed it may eventually become necessary to certify the isolation of access to raw data captured by RAS.

Modularisation of RAS systems is considered one way to accelerate uptake through reduced cost and increased flexibility. However it presents challenges in reliability of all module combinations and how to identify the interfaces where security protocols can be implemented.

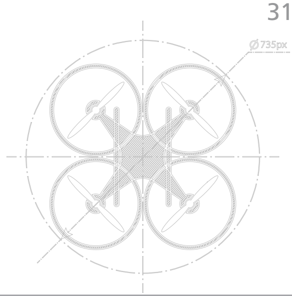
Any breaches of data privacy at this level can create significant issues: data gathered by domestic robots providing information about valuables in a house, workplace robots gathering personal or performance related data about individuals.

Few people understand the value of the data that they provide over the internet, but at least they may be aware that they are volunteering this data and perhaps understand that there is the option to ‘disconnect’. The capture of data using RAS will not involve such implicit consent and the continuous stream of data captured from autonomous systems can enable a far greater assessment of personal activity.

Data privacy guidelines will need to be created and enforced that set out what is an acceptable use of RAS data, what can and cannot be communicated, and to establish when data should be attributed to an individual, and when it should not. When everyone encounters multiple RAS every day, trust in the gathering and processing of information will become a major issue.

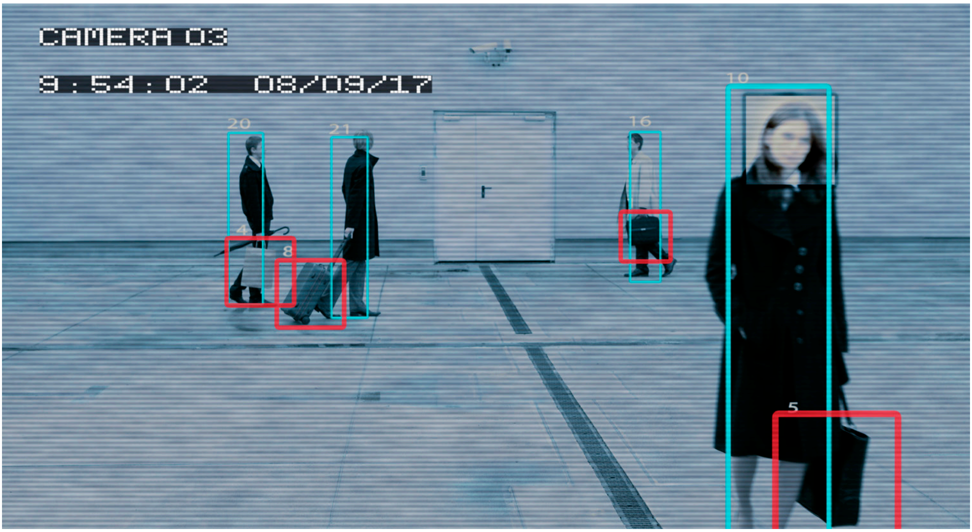
Knowledge privacy

The concern with primary data is only part of the privacy issue that surrounds RAS gathered data. This primary data can be processed over time to provide information about the local environment, for example knowledge of when a house is occupied, or where the owner leaves their car keys. It is expected that in the future these abstract inferences will become more complex and sophisticated to the point that a RAS is generating knowledge about the individuals it encounters, for example knowledge about the way a particular worker carries out a task, what clothes they wear or what food they eat. Current systems in laboratories are only just starting to be able to develop this type of knowledge, knowledge that goes beyond the identification of obstacles and objects. Clearly there are significant privacy and security



issues inherent in the acquisition of such knowledge especially since it may be owned by a third party such as the robot manufacturer. Certain kinds of data may be extremely valuable both with regard to personal security but also with respect to the performance and habits of individuals.

The codifying and communication of this kind of detailed knowledge about people and place produces a second level of concern about privacy. First how can we guarantee that the knowledge generated is accurate, and second, how can that knowledge be used to make decisions that do not compromise privacy. One critical aspect of these issues is validating the identity of the individuals the robot interacts with.



Data and knowledge integrity

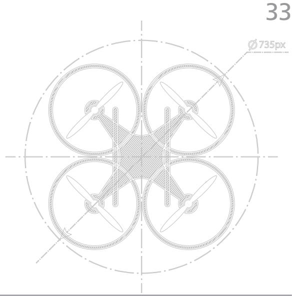
A further aspect of data security concerns the accumulation of data such that knowledge increases without compromising privacy by false aggregation. Assessing the integrity of information interpreted from data gathered by RAS presents a challenge as does assessing the integrity of knowledge developed from that information. There is a danger that knowledge built on information derived from primary data may build a false picture and that decisions made may then be based on inaccurate information. If this involves data from multiple RAS then verifying the integrity of the knowledge generated will be critical to making the correct decisions. This leads to the problem of 'who checks the data checker'. Once again there are opportunities for tools that manage data provenance and accuracy, which may rely on identifying correlations between different sources of data to reinforce categorisations and decisions. Trust in RAS is thus not only about physical safety but also about trust in the way that data is gathered and how it is used, communicated and processed.

Public good

While privacy issues are often seen only from a personal perspective they apply fully to commercial data and the development of knowledge about companies and commercial interests. But here there is also an issue of public good. When a critical system fails each component will collect data about itself. There will be useful information spread across this data stream, information that may point out liabilities or help the prevention of accidents. However this data will belong to the individual component manufacturers and suppliers and they will be reluctant to allow full access to such information if it is connected to liability or issues of reliability. Companies will be every bit as sensitive about their data privacy as an individual. Because this data has public value in assuring safety a balance must be negotiated between public and private good and the setting of rights and responsibilities. As in the public case an independent trusted organisation may be needed to act as a filter and disseminator of information that has public value, perhaps trading anonymity for data.

Because this data has public value in assuring safety a balance must be negotiated between public and private good and the setting of rights and responsibilities

Standardising the flow of knowledge and data from the multiple RAS that might constitute an operational structure, such as an oil refinery, will make reconstruction of failure events easier as data will be held within a common structure and thus more easily correlated. On the other hand this standardisation of knowledge will also allow the development of certification processes that can provide privacy guarantees. There must therefore be a careful balance between knowledge



standardisation and the maintenance of privacy resulting from the aggregation of knowledge. There is therefore a need to address public good vs privacy issues with respect to the communication of data and knowledge from RAS devices and this needs to be achieved during system design. Indeed the provision of secure platforms and protocols may be a significant growth area in the future.

Work should be focused on these issues, and the need to provide checks and balances on the public value of data and on the possible need to licence or regulate data gathering, in order to ensure that the public value can be extracted from it. RAS will be critical to both the capture and use of such data and its eventual ubiquity and capture of data without consent represents a challenge that must be addressed. The goal must be to create a framework of regulation and assurance that creates trust in RAS.

A license to use RAS

It is now recognised that while individual data elements may be collected or processed anonymously there is an increasing ability to reconstruct and join multiple data sources to reverse engineer anonymity. Blanket bans on data capture will restrict the market, yet enforcing regulation at a detailed level within big data resources may prove incredibly difficult. Added to this is the open question of what to regulate. Regulating technology can be a difficult exercise as rapid technical advances outstrip the ability of regulation to remain relevant, as can be seen with current data protection legislation[12] lagging behind the rapid advances in big data, machine learning and the internet of things. Greater success seems achievable in the regulation of applications, medical, transport, marine etc, but even here care must be taken not to restrict the market through over regulation, with the onus not on pre-regulation but a reliance on the augmentation of existing legislation, contract, product, consumer, liability etc, when the need arises.

Management of autonomous adaptation

A RAS behaviour will come from its onboard planning system that selects one or a series of connected actions to execute to achieve a goal. Typically these ‘atomic’ and indivisible actions (or ‘behaviours’) are fixed and merely parameterised using data from sensors (for example, x,y,z location of object to reach). Any changes in the RAS behaviour only come from changing the sequence of actions executed and the parameters involved. However, as noted above, RAS can learn. In principle they could start to adapt the contents of fixed behaviours that

[12] https://secure.edps.europa.eu/EDPSWEB/webdav/site/mySite/shared/Documents/Consultation/Opinions/2015/15-11-19_Big_Data_EN.pdf

routinely fail. This is potentially a very powerful tool for a RAS operating in an unknown, unstructured environment. However, it is difficult to assure and certify because there is typically no governance as to what is learnt and therefore no predictability about behaviour in given circumstances. Researching how to assure systems that adapt and learn is therefore important.

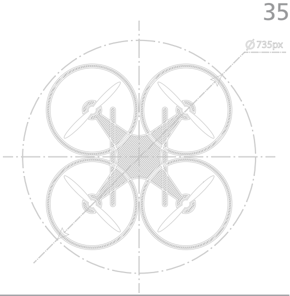
Ethical and moral design

As mentioned above there are human, ethical and moral factors inherent in certain types of RAS decision making. The example of an autonomous vehicle choosing who should take the impact of a crash is often given. And there are also safety and privacy issues about data collected. These ethical and moral dimensions ultimately raise significant questions about best practice in design and how ethical and moral dimensions in RAS decision making can be coded into systems.

Key points

- Safety must be 'by design', but the complexity of interactions between multiple RAS systems means that ensuring system safety will depend on standards and clear understanding of the implications of modularisation.
- RAS present two types of safety issue, physical safety and data safety.
- Where the operator is not required to continuously engage in a task, in the event of a failure or an unexpected event humans may not be able to re-engage and regain situational awareness fast enough to be the system of last resort for a safe recovery.
- Data and knowledge privacy and integrity guidelines are needed to create and enforce what is an acceptable use of RAS data and knowledge. Privacy should be balanced with public good.
- If RAS are to make critical decisions it is important to ensure that the knowledge on which the decisions are based is accurate and, where relevant, individuals can be accurately identified.
- It may be difficult to safety-certify systems that learn and adapt.
- There are human, moral and ethical factors in certain types of RAS decision making. A dialogue is needed to elaborate guidelines and best practice.

Public awareness and trust



Without public trust in RAS the market will not develop. However, in the midst of technical complexity, people increasingly use systems they do not understand and therefore do not trust implicitly. This breakdown in trust will lead the public to demand assurance that systems are safe to use.

To many there are just two views of what a 'robot' is: the robot-arm building cars and the humanoid robot as both toy and destroyer of humanity. For some these images of robots nurture fear - a fear that jobs will be taken, and a fear that humanity will be dominated by robots, stronger, faster, and more intelligent than they are. However experiments[13] of human behaviour towards robots is more positive. It indicates we readily adopt them as a kind of pet, and even anthropomorphise them, affording them the same rights as humans. Empirically this has been observed in domestic robots including vacuum cleaners and lawn mowers and also in new generations of companion robots.

Trust in AI and robotics will take effort, evidence and time to build. It is possible that only when people start to encounter robots will they understand the benefits. This report focuses on the safety benefits to society from RAS, but these benefits can only be realised by societal consent.

Building public trust

The complexity of RAS means that building public trust may require intermediaries whose role is to provide the evidence for trust, to guarantee confidence in the complexity, to reassure the public that systems are safe to use, and to provide guidelines and set boundaries.

Work is needed to carefully explore how trust can be developed and guaranteed. It is partially about appropriate regulation but it is primarily about public perception and reassurance. This is a global issue and to address this across countries and cultures, where despite globalisation there are extensive differences in attitudes to RAS, will require clarity of communication and sensitivity to cultural norms.

The need for trust does not stop with the RAS. Trust must extend beyond the device to the companies and service agencies that install, maintain and control RAS. This requires a holistic approach to trust, to privacy, to data ownership. The boundaries on data capture and usage must be clear and clarity on ethical practice should underpin regulation. To implement this trust it must be at the core of design and coded into the sub-systems and modules that make up RAS.

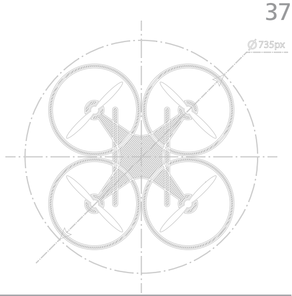
[13] http://sfussell.hci.cornell.edu/pubs/Manuscripts/Fussell-HRI08.pdf

Building messages and allaying fears

As RAS has become more widely discussed the public image is less formed by science fiction and more so by economic and social arguments framed by the media, often taking a negative, sensationalist viewpoint. RAS has the potential to become an emotive subject with strong views expressed against the inevitable downside inherent in any new technology. Care needs to be taken to avoid embedding negative stereotypes about both AI and RAS.

While it is important to balance messages about RAS, by examining both risks and benefits, it must also be made clear what RAS cannot do, as well as what RAS should not do. It is important to clearly communicate the limitations of both current and future technology and to place emotive arguments in a more technical context.

There is a real danger that clear messages about RAS will become lost in the complexity of the arguments and that as a consequence the lasting perception becomes negative and mistrust ensues. Clear communicable messages about RAS are required that are comprehensible and are in themselves trustable. In discussing and developing public awareness and trust in RAS the ability of RAS to empower people and organisations to improve and progress is paramount.



RAS has the ability to improve decision making and actions together through its potential for human-like physical interaction with the real world in a wide range of applications. The potential benefit to society both socially and economically is extensive but not without consequences.

As with any new technology there will be unintended consequences of its application. These will often shape the day to day messages and opinion about RAS. However the potential for long term positive impact of RAS is significant and some of its consequences will take a decade or more to surface. In this context it is important both for industry and society that there are clear and independent organisations able to assure safety and build trust in RAS.

RAS and the workplace

RAS has the potential to alter working relationships between employer and employee by changing the skill mix needed to carry out a task. Employers will be able to deploy RAS as co-workers, which may change the employee-employer relationship, or they may choose to replace workers with RAS. In addition employers will be able to collect and collate data through RAS about performance and process providing far more data than is currently possible. These changes raise fundamental questions, for example: What rights does a worker have over a skill that a robot has learned from them? Does replacement by a robot count as discrimination and what rights do workers have where jobs are replaced by robots to increase safety, or create higher productivity or extend working life through physical augmentation. It is clear that the introduction of RAS raises key issues related to the nature of work, individual rights and the need to ensure high levels of competitiveness.

Work is needed to examine the broader aspects and impact of RAS on employment, not just from an economic perspective but from a social and organisational perspective. There is a strong need to focus on the quality of work and nature of work in the RAS age.

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Ethics

Almost every area of RAS application raises ethical issues. The decision making capability of RAS coupled to its physical interaction places it within the human sphere in a way that no previous machine has been. RAS will make decisions that humans depend on and some of those decisions will have an ethical dimension: from decisions made by autonomous vehicles about how to minimise the effects of a collision to ensuring the elderly and vulnerable are treated with respect by RAS enabled care systems. There is open debate on how, and indeed if, RAS can make value judgements that are acceptable and ethical. While ethical design practice is starting to emerge, even basic questions such as 'should RAS be banned from exhibiting deliberate deception?' are fraught with exceptions.

Work is needed to establish global norms of ethical practice and to create guidelines and best practice examples that might in the long term be encoded into the design process. However, in order to have impact and relevance such an endeavour must focus on what RAS is capable of in the near to medium term.

Key points

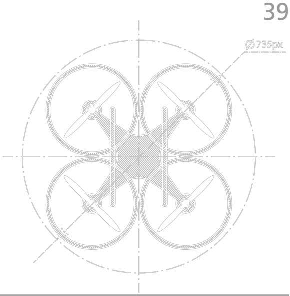
- This report focuses on the safety benefits to society from RAS, but these benefits can only be realised by public consent. Public trust should extend beyond the RAS itself to the companies building RAS and providing RAS services, and to regulators and governments.

- Clearer communication and better public understanding is needed, and the media has a role to play in this. Work is needed internationally to understand and develop trust in different cultures and countries.

- RAS will change the nature of many peoples' jobs. How this is addressed and mitigated will be a strong factor in societal acceptance.

- To see the benefits from RAS we need a mature public dialogue on their benefits, risks and ethical frameworks.

Developing key skills in robotics and autonomous systems



Workforce

Introducing RAS into the workplace will result in skill shortages. There is already a shortage of skilled workers within the current work force and within the research and engineering skill base. RAS requires different operator skills and different installation and integration skills than are required in a non-RAS industry. Industry cannot hope to adopt RAS without revising its skill base. In the service sector RAS will cause disruption. It will enable new business models and will alter how services are delivered and used. It will also up-skill some workers changing the level of work they can do by shifting the baseline of skill required for certain jobs. For example, if RAS is to impact on small and medium enterprise (SME) manufacturing the skills needed to create and install SME manufacturing solutions using RAS must be developed within the SMEs themselves aided by tools and modular systems designed for simple integration, configuration and operation.

Work is need to establish the likely skill mix and more importantly the change in skill mix that the introduction of RAS will bring both in manufacturing, particularly in small and mid-scale manufacturing, and in the service sector.

Education and skills

The skill impact will be felt at all levels of expertise from shortages of researchers to shortages of technicians and skilled operators. It is difficult to state the extent of the impact as it will depend partly on the speed of RAS uptake but it is highly likely that, for some developed counties in particular, skill shortages may restrict how RAS are deployed.

The production of skilled RAS practitioners at degree and post-graduate level relies on a sufficient skill base in high school leavers to feed it, and on being able to attract that talent into RAS. RAS competes with other sectors such as the financial and other ICT based industries who are similarly short of skilled workers.

STEM uptake in schools is important to seeing an increase in skills in the workforce.

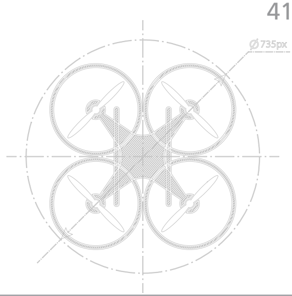
Teacher knowledge has in general lagged behind technology development. Few teachers are able to teach engineering, RAS or design. However RAS, through the appeal of its hands on physical interaction and its societal application, has a particular ability to engage creatives and promote the joining of technology and the arts, exemplified by the design-coupled engineering focus of companies such as Dyson and Apple. This has the potential to play a critical role in increasing the profile of 'makers' essential to the creation of RAS and widening the skill base particularly amongst school leavers.

Work is needed to create continuing professional development (CPD) in engineering and design for teachers at all levels including primary education that can enable and empower teaching. Schemes such as Robokids[14] where all students are engaged instead of a select few are exemplary.

Professional development

In addition to this fundamental building of basic skills there is a need to raise RAS skill levels within the technical professions. As the impact of RAS becomes more pronounced engineers and technical staff will need training to ensure that industry and the service sector can make full use of the advantages RAS offers. RAS is a broad technical discipline and involves skills in integration and systems design that many current professionals will not have encountered. It will be essential to re-skill professional and technical staff.

[14] http://www.robokid.org.uk



Key points

- The introduction of RAS will set requirements for new skills and require increased numbers of higher skilled workers.
- Skills will be required at all levels from researchers to operators.
- Work is needed now to ensure the uptake of STEM in schools is increased so that the deployment of RAS is not limited by the skill base. This includes training and support for teachers.
- The impact of RAS will be felt across both manufacturing and the service sector where disruption of business models will cause skill requirements to shift and change.
- Policy makers need to engage with the potential impacts of RAS, which will vary from country to country, particularly to minimise the social impact of job displacement.

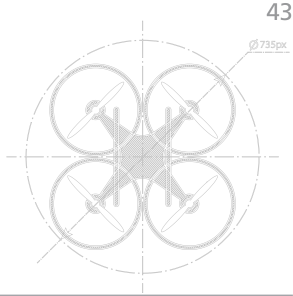
Creating the tipping point

This report focuses on the potential safety benefits of RAS. However to realise these benefits RAS need to be commercially viable. RAS will not reach the 'tipping point' for investment until the commercial and technical risks are reduced to a point where investors and corporations agree to engage. In order to create a viable market it is essential that RAS applications and technologies reach the point where private investment dominates in the development of new technologies, services and applications. Public funding will continue to be necessary in order to support infrastructure and cross cutting activities such as fundamental research, the development of regulation and standards as well as to provide stimulation for new areas of innovation and application.

There are many different factors that need to come together for any individual RAS application to reach that tipping point: technology needs to be mature, the market return well understood, the regulation, validation and testing of systems well established, and finance structured appropriately to the needs of each market. Well structured finance is particularly important in the service sector RAS do not operate in isolation and require co-investment in infrastructure and facilities to bring RAS to market. In a number of applications the introduction of RAS will require 'generational change' and therefore significant investment to enable that change. Such large scale step changes require low levels of risk before investment can be secured.

The early stage nature of RAS and its autonomy means that currently RAS carries greater investment risk than technologies where markets are already established. In most potential markets these risks are seen by investors as currently being too high and therefore RAS cannot reach the tipping point. In these circumstances public investment is required, either in terms of direct investment or investment in infrastructure or regulatory frameworks that can directly reduce the technical risk and thereby increase the likelihood of private investment. However in focusing public investment it is important that the value of that investment is carefully considered to ensure that it can have real impact on the chosen market or technology.

RAS will not reach the 'tipping point' for investment until the commercial and technical risks are reduced to a point where investors and corporations agree to engage

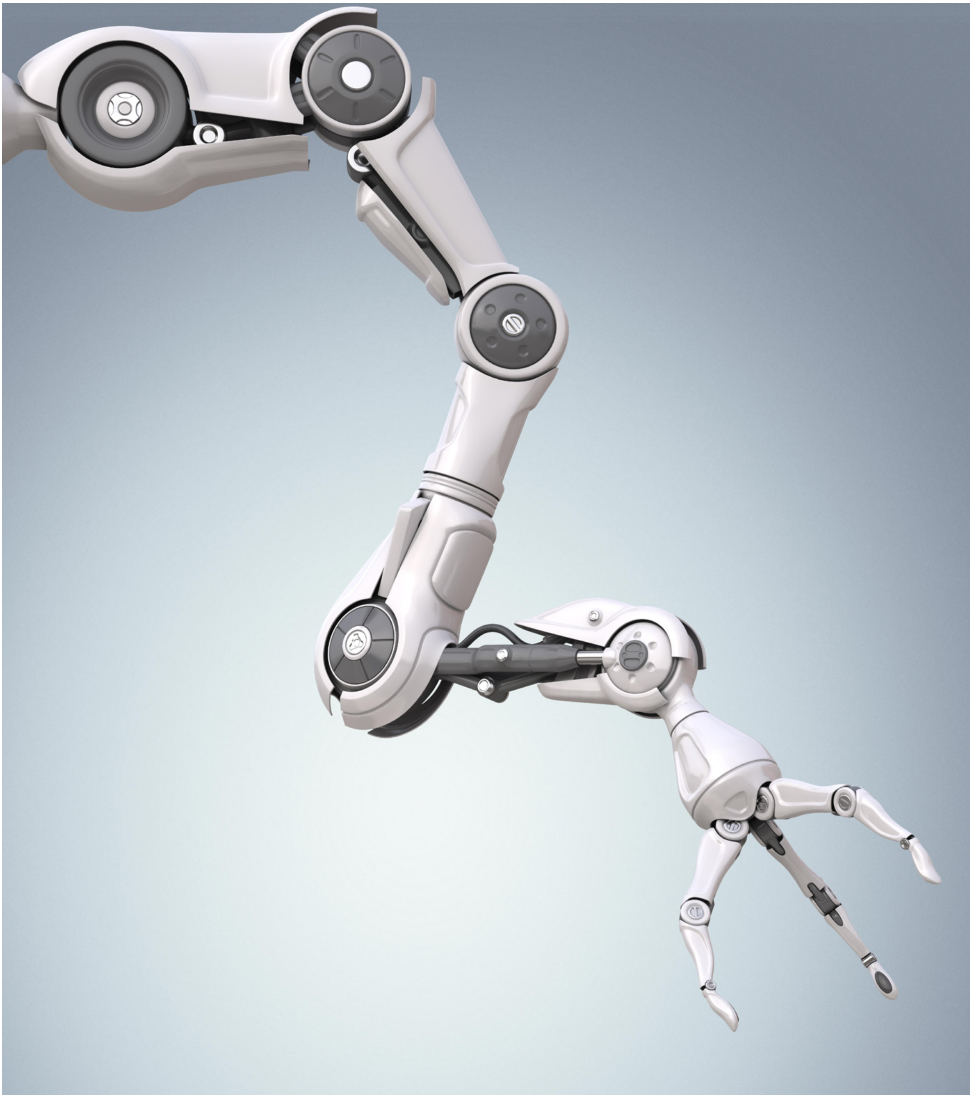


Developmental risks

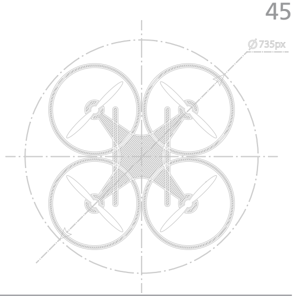
Where RAS interacts with people, where RAS delivers safety critical services, or is an integral part of public or civil infrastructure the risks inherent in RAS must be well understand and managed. The primary risks come from the autonomous decision making that is an integral part of RAS. Building trust in the operation of RAS comes from the delivery of trust by design coupled to testing in real environments. While it may be possible to develop testing and certification methods that create partial confidence whole system testing is still regarded as the only way to validate the operation of a RAS. Thus the development of testing infrastructures is seen as a critical investment in bringing of RAS to market.

Building beneficial frameworks

In order to stimulate investment in RAS and to overcome the complexities of early stage deployment it may be necessary to provide RAS-specific incentives to investors. It may also be necessary to create broad testing arenas where special localised regulation allows greater use of RAS in everyday or localised environments. For example a town, hospital or airport where RAS is installed and scrutinised in order to provide a high level working model of what, eventually, might become common place at a national or global level. Early development of these beneficial frameworks will encourage investment.



RAS timelime



As with other major technical advances RAS will pass through three phases: today the sight of a robot in the street causes everyone to stop and stare, excited by seeing a robot in a public place. In factories robot arms are common place in certain industries, but in many areas of manufacturing they are still a novelty. In hospitals the use of robot tugs is still in its infancy and while we are now accustomed to robot vacuum cleaners these are no longer seen or even marketed as ‘robots’.

In 10 years or so robots will be more common, many, such as self-driving cars, will not be seen as robots but as cars that do not need a driver. Exoskeletons will not be seen as robots any more than drones are today, and yet the technology that has made them possible comes from robotics. This is the same as current smart phones, if a smart phone was transported back in time to 1980, it would be seen as the most incredible AI machine: speech recognition, vision recognition, semantic processing, natural language understanding, 3D models, Pokemon-go. But today no one sees a smart phone as AI. There will still be some robots that attract attention, robot football teams, robot waiters, robots able to interact and collaborate with us in tasks, but by 10 year’s time they are becoming more familiar.

Finally robots will enter a third phase maybe 15-30 years from now where they just seem like any other piece of technology, they will have entered the fabric of society the disruptions and new business models will have happened and we will have worked through the extended side effects of societal impact. Children will grow up with robots just as our children have grown up in the social media age. Generation R will think nothing of a robot clearing up at home or taking them to school or maybe even teaching them. We as old people we will rely on robots to extend our well being and watch out for us as we forget where we put our glasses, or keys, and protect us from falling.

There are a series of timelines on the following pages under the headings of applications, impact and scientific underpinnings.

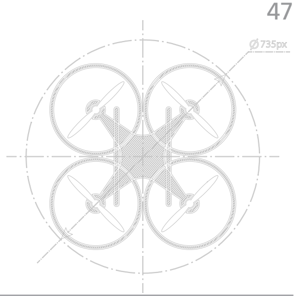
RAS: Future timeline - Applications

0-5 yrs

- Inspection tasks augmented by RAS
- Incremental improvement in autonomy application in transport
- Hospital logistics sees increased use of RAS
- Prosthetics become more capable and controllable
- Active exoskeletons increasingly common in rehabilitation
- Companion robots are commodities, mass produced with falling prices
- Connected RAS trusted in safety critical applications because of cybersecurity features

5-10 yrs

- RAS able to carry out basic maintenance tasks on assets and infrastructure with increasing ability
- Short distance urban, on-demand RAS based transport rolled out as a service
- Farming, both arable and livestock see rapid increase in RAS based methods
- Domestic RAS able to fetch and carry items from surface to surface providing increasing levels of domestic assistance
- Logistics RAS able to pack and unpack vans and containers at human speed
- RAS UAVs able to land and take-off at specially selected commercial airports, using the same runways as passenger aircraft but different approach and take-off corridors
- RAS starting to be used for some last mile delivery applications
- RAS increasingly used in retail and hospitality industries
- On-demand food production uses high levels of RAS to improve quality and consistency of products, e.g. pizza production. Provides novelty value in food retail
- RAS used in basic medical assessment in GP surgeries
- SME manufacturing increasingly adopting RAS as a part of new manufacturing processes
- Increased use of RAS in rehabilitation
- RAS augmented surgical tools becoming more widely used for diagnosis and minor procedures
- RAS used to augment healthy ageing, dementia care and elderly care start to become economically viable

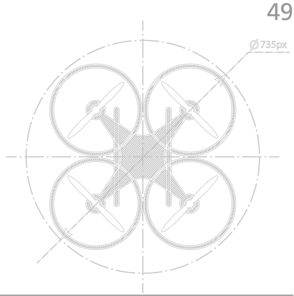


RAS: Future timeline - Applications

10-15 yrs

- Autonomous vehicles able to navigate city streets available
- UAV and RAS ground transport regularly used for last mile delivery in cities
- Domestic RAS able to carry out most kitchen tasks, high end kitchens all include standard RAS enabled appliances and fittings
- Early RAS-enabled homes self-clean, organise and maintain
- Some basic inspection and maintenance tasks on assets completely carried out by RAS
- Some farms almost fully operated by RAS
- Hospital logistics now based on RAS in all new build hospitals
- Supermarkets and retail widely use RAS to increase re-stocking efficiency
- Some eye surgery carried out with surgeon supervised RAS, without tele-operation
- First humanoids able to do useful work for realistic periods
- RAS use simple narrative and dialog to brief and debrief their plans and activities
- Maker centres offer bespoke RAS parts replacement using quality 3D printing
- RAS hardware increasingly commoditised. Shared knowledge services allow 'apps' to provide RAS behaviour and human-robot interaction functions

RAS: Future timeline - Impact
0-5 years
- RAS impact in manufacturing increases, collaborative tasks and in intra-logistics and warehousing - Continuing quality of life improvements for prosthetics users - Rehabilitation more effective for those who can afford it - Greater acceptance of RAS by the public though adoption of companion robots as pets and acceptance of shared autonomy in vehicles
5-10 years
- RAS more visible to general public - RAS has measurable impact on frail elderly living at home - Public more aware of RAS gathered data and issues of privacy - RAS specific case law enables new judgements. First RAS service companies sued for inappropriate data use - Measureable reductions in cost and downtime of asset operations - Cost of rehabilitation robots fall
10-15 years
- Cities start to restructure around RAS enabled transport - RAS commonly used to augment care in the community for frail elderly - RAS starting to become commonplace and invisible - Some soft robotics products enter the market - Increased trust in conventional RAS through adherence to widely accepted ethical frameworks and self-certification; concerns about privacy remain - RAS startups from the mid 2010s become major corporations - RAS studies becoming mainstream as part of computing in school curricula



RAS: Future timeline - Scientific underpinnings

0-5 yrs

- Improved all weather sensing
- Basic multi-modal user interaction generally available
- Ever improving control systems and perception through machine learning
- Standards for open knowledge services start to emerge
- Regulations for RAS use in different sectors start to emerge, including privacy
- Cybersecurity and distributed ledger integrated into RAS

5-10 yrs

- Dependable grasping and manipulation becomes available
- Human speed mechatronics available
- UAV anti-collision systems validated
- Programming by demonstration becomes viable in constrained applications
- System dependability improves to all day operation
- 3D printing produces bespoke parts to sufficient quality
- Energy aware RAS architectures bring increased endurance during autonomous operations
- Assurance processes for learning systems emerge
- Open data and knowledge standards are adopted while closed commercial systems compete

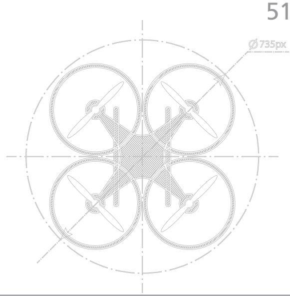
10-15 yrs

- Neuroscience research brings dividends in machine learning computational structures
- Synthetic biology and RAS come together to build first bespoke biological robots
- Ethics debate reaches fever pitch on prospects of biological robots
- Quantum computing offers greater computing for RAS AI
- Smart materials with greater embedded sensing and actuation lead to ground breaking embodiments
- 3D printing of biological components becomes a reality
- New mobile energy generation and storage technologies increase RAS endurance

Findings and recommendations

Research and development in RAS is proceeding at pace through public and privately funded programmes predominantly in Europe, Asia and North America. These programmes address much of the sensing, control, planning, embodiment, human interface, and collaboration technology to realise these new and smarter tools. However, there are some important areas which need addressing if we are to see the safety benefits from the implementation of RAS, and where the Foundation may be well positioned to lead or support other international efforts.

Suggested priority areas			
Openess and sharing	Assurance and certification	Security and resilience	Public trust, understanding and skills
Open data standards	Asset self certification	Cyber security of RAS	Ethical and trusted RAS frameworks
Open data sets	Assurance of RAS learning systems	Software system integrity	Assured skills for RAS
Shared curation of RAS knowledge			



Openess and sharing

- Open data standards
  The collection, curation, storage and analysis of asset data will require standards and a metrology that cut across sensors, assets, asset classes and organisations, and will need to consider the security and corruptibility of data at any point in the data lifecycle. Sharing data improves knowledge and integrity, saves lives and encourages competition. Open data standards make this technically feasible and are needed to facilitate data sharing for aggregation and re-use. A body could be set up to investigate the development of cross industry open standards for RAS based data to be collected and used. This should include development or monitoring of semantic ontology standards representing cognitive knowledge about asset conditions. It should also investigate how data privacy can be maintained and how asset class inspection can be enabled to enhance safety.

- Open data sets
  Researchers can make progress with and compare techniques for asset assurance and RAS operation given, common open data sets about infrastructure condition. Work is needed to pursue the collection, curation and any anonymising of large asset-integrity data sets with ground-truthed failures as a resource for 'public' researcher use, to identify an 'honest broker' for data ownership and to support them in a trial to make big data about a class of asset. This may require a club approach among data owners. Data and knowledge privacy and integrity guidelines are needed to create and enforce what is an acceptable use of RAS data and knowledge, recognising trade-offs between privacy and public good.

- Open curation of RAS knowledge into services for smart spaces
  An open and standard platform technology is required to make availableknowledge services to RAS-of-opportunity so that they can access maintenance data, procedures and predicted areas requiring inspection or maintenance attention under operational conditions. This enables the RAS to perform inspection or intervention functions within its sensing and actuation capabilities. It also enables generic RAS hardware and software through 'apps' that use these knowledge services. Benefits include reduced RAS development time; increased flexibility of use in the field; representation, elicitation and curation of knowledge (as opposed to data) to enable the RAS to perform tasks; and real-time optimisation of what data to collect and how according to perceived events. Finally, links from these knowledge services to through-life asset design, including condition monitoring, should be explored to realise 'smart spaces'.

Assurance and certification

- Self-certification approaches

  Self-certification and assurance of an asset under operational conditions using RAS is a potentially disruptive development that could change the way the assurance industry does business. It therefore requires some activity to further study its feasibility and potential impacts. In particular, what levels of assurance and increased safety can this approach achieve. As part of this, dialog is required to study the effects of a possible self-certification capability on regulatory bodies and the perception and reality of risk and costs.

  In addition the core challenge of how to guarantee the integrity of the complete asset, including the RAS working on it and any condition monitoring systems, requires further development.

  A small exemplar study of integrity management under operational conditions would rapidly demonstrate the potential and the pitfalls.

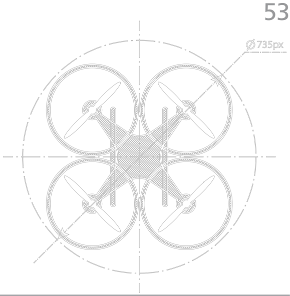
- Certification of learning systems

  Certification and assurance typically depend on a specification of system performance and state against which tests can be made for validation and verification. However, where a system contains components that learn during operation, there is the possibility it will learn things that undermine the key performance measures that verify its safety. It is not clear how to then offer certification and assurance on RAS with learning systems. One approach is to only learn off line: switch this off, carry out the verification and validation tests for certification and then leave the learning switched off. However, this loses some of the potential of the technical approach. The situation is further made challenging in highly unpredicatable environments. How can a RAS be verified when it faces unknown situations? A more detailed investigation into this is required.

Security and resilience

- Cybersecurity and RAS

  The cybersecurity and RAS research and development communities need to work closely. Some scoping activity could identify the opportunities and the needs in this area, to secure network connected RAS against a variety of classes of intrusion. This may include the need for encryption and the design of efficient approaches, including the role of digital ledger technology for guaranteed transaction records. Such RAS could be publically offered in a hack challenge to test their security.



- Software systems integrity management
  Ideally, RAS software will be developed to acceptable software integrity level standards, appropriate to the criticality of the application. This is not a cheap endeavour. Identifying and recomending cost-effective ways to do this will encourage adoption by developers and specification by customers. Allied to this is the embedding of fault detection and diagnosis as part of the RAS onboard health management, with acceptably low false alarm rates. Third party vendor software embedded as libraries should also be assured or at least firewalled and jacketed so that the RAS degrades gracefully, predictably and safely in the event of code and other errors.

Public trust, understanding and skills

- Development and monitoring of ethical RAS frameworks and public trust
  Engineers alone should not be left to programme behaviours into robots that cross ethical boundaries. Nor can machines that learn be similarly empowered. Internationally agreed ethical standards for RAS are needed so that clear guidance and norms evolve, for example for ‘no-win’ decision making. A culture of ethical concern should be encouraged across the international R&D community.

- Assured skills for RAS
  We will need more RAS skills at all levels in the future, and more people who possess them and are passionate. Teachers need support to lay good foundations in schools, with examples such as Robokid offering good quality distance learning materials and access to maintained equipment. Undergraduate, postgraduate, continued professional development and fellowships all continue to be needed. Secondments for RAS students and researchers into the assurance industry would also provide useful mutual transfer of knowledge and skills.

These recommendations are mostly in the area of the assurance of autonomous systems. This is because there is ‘white space’ where the Foundation can bring additional value. However once progress is made in the assurance of safe autonomy, there will be knock-on implications for the future design and build of the software and hardware aspect of RAS.

Appendix A: Contributors

Contributors responding through the open consultation process

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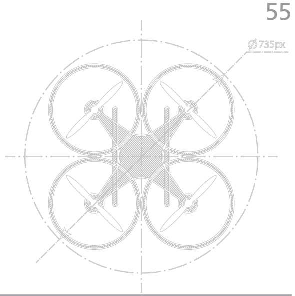
Appendix B: Some ideas for short-term activities



During the workshop and consultation a number of possible quick win actions were suggested as potential routes to impact in this area. These included:

- Prize competitions: for example, addressing near term problemsidentified by industry specialists. To include press coverage to raise awareness and public perception
- Event Detection in Data: With big data available, or at least validated models, support research in machine learning for event detection
- Multi-modal affective human-machine interfaces: Develop some demonstrators illustrating how operators work with RAS-based asset integrity measurements and processes. Intuitive easy to use interfaces that work alongside operators are key to adoption in user-world.
- Process development: Develop processes that trained users and programmed robots can follow to carry out integrity management. This will provide use cases for task scoping.
- Living laboratories: Establish living laboratories for demonstrations, de-risking, competitions, outreach and public awareness, sales, and training. Use a joint venture approach to development. Some testbed ideas where RAS approaches to asset protection and risk reduction can be trialled, for example through joint venture, including major infrastructure investment such as: naval ships; new build metro and rail systems; government infrastructure projects; decommissioning plant; nuclear new build; and assets subject to UAV inspection.

This will allow additional exploration of important topics, such as:

- Engaging with the supply chain to demonstrate a value proposition as better, faster, cheaper to help adoption
- Inclusion of legacy technology is an important part of any proposed approach
- How to demonstrate and trial without interfering with the assets primary purpose
- Business cases and roadmaps: develop a technology roadmap and some exemplar business cases to showcase to asset operators, investors and innovators.

Appendix C: Further reading

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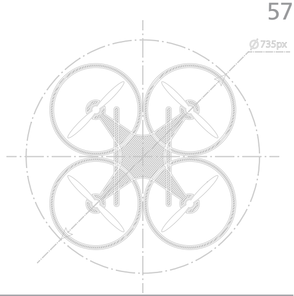

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25. Robotics 2020. Strategic Research Agenda (SRA) For Robotics in Europe 2014-2020. Eurobotics aisbl, Brussels

26. Robotics 2020 multi-annual roadmap (MAR) For Robotics in Europe Horizon 2020 Call ICT-2016 (ICT-25 & ICT-26). Eurobotics aisbl, Brussels. (Dec 2015)

27. New Robot Strategy - Japan's Robot Strategy - Vision, Strategy, Action Plan - The Headquarters for Japan's Economic Revitalization (Feb 2015)

28. Manufacturing robotics The next robotic industrial revolution UK-RAS Network White Papers (2016)

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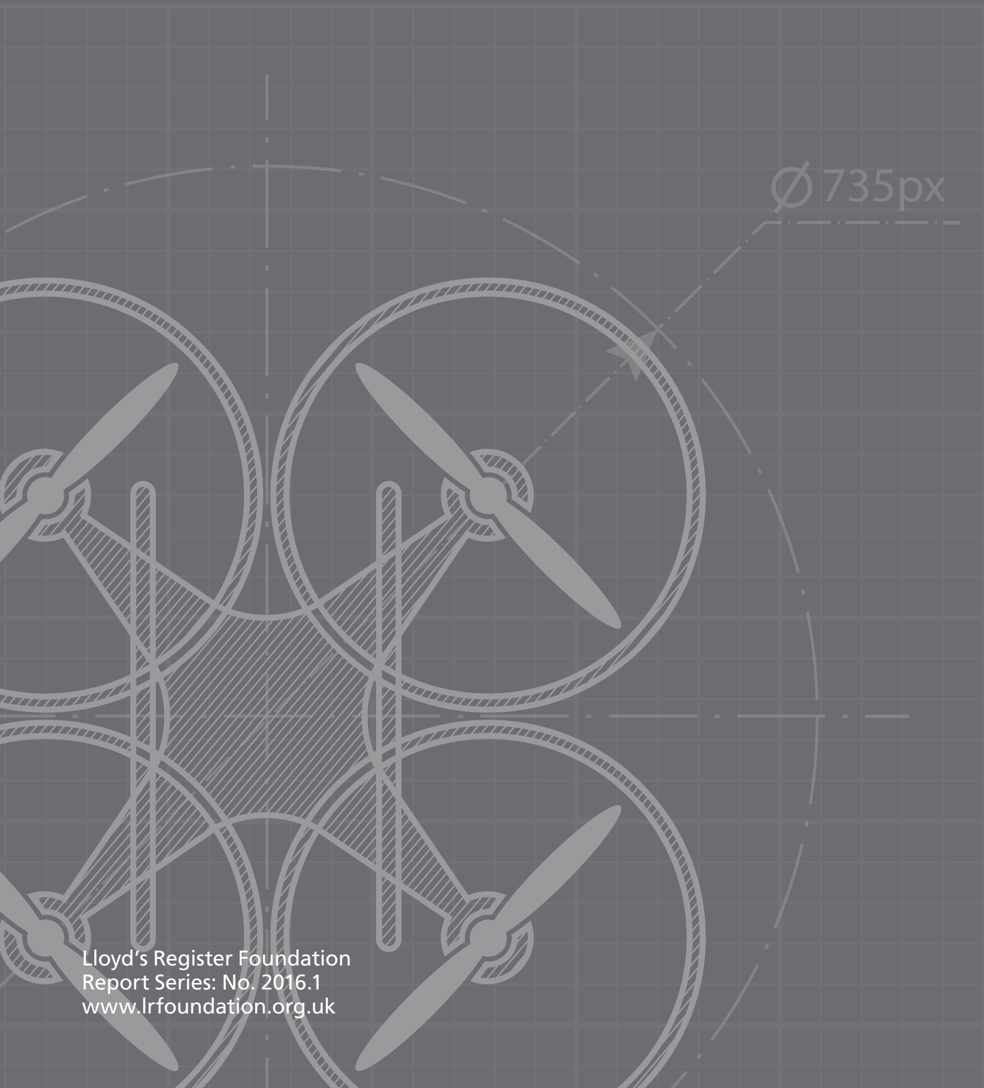

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