Robotics Horizon

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Foreword

The Rt Hon David Willets, minister for Universities and Science identified the importance of Robotics and Autonomous Systems as a general technology: '*Robots acting independently of human control - which can learn, adapt and take decisions - will revolutionise our economy and society over the next 20 years*' (Willetts 2013).

The current report has the focus on the societal aspect of this revolution and briefly sets out the landscape of current and future robotic systems applied in everyday human life and offers a brief overview of what robotics currently is and might be about in the future. The report includes contributions from across the UK robotics community (though completeness is not claimed).The emphasis is on the application of robots operating in the vicinity of human beings that can learn, adapt and take decisions. However, the underlying enabling technologies such as machine vision, machine learning and artificial intelligence are not discussed separately.

Though important, the foreseen prospects of robotics are not limited to robots collaborating with humans. In parallel with the writing of the current paper, the Robotics and Autonomous Systems (RAS) Special Interest Group is aiming to develop a roadmap with a major focus on defining a vision for an emerging (UK) industrial Robotics and Autonomous Systems sector. In this vision the distinct enabling technologies will find a prominent place.

The current robotics horizon paper is best positioned as additional to the RAS roadmap and provides a view on major 'long term' problems occurring in everyday human environments that have to be solved in order to enable the envisioned robotics revolution to take place.

Executive summary

'*Robots acting independently of human control - which can learn, adapt and take decisions - will revolutionise our economy and society over the next 20 years*' (Willetts 2013).

Part of the robotics revolution is that it is widening the area of (possible) robot applications; robots are getting out of the labs and industrial plants and are entering everyday life situations. Thus, robotics which conventionally was in the domains of engineering and computer science is involving a widening spectrum of specialists from many disciplines such as biologist, psychologist but also heath and care specialist.

Robotics: not only technology

Industrial automation and robotics aims at fully automated production and a primary issue concerns the limitations of the technology. However in areas where robots are to assist human beings, the quest is not just for technological perfection, equally or even more important are questions concerning what tasks can but also may a robot perform, who controls the robot and how much autonomous decision making may be granted to a robot. These questions pop up immediately in (often negative) public discussions concerning the application of robots as lethal weapons in a military context (Sciencewise 2013) and tend to impact other application domains as well. In order to clear the way for public acceptance, these issues have to be clarified, in particular for robots that are applied in private (human inhabited) spaces. For instance in care applications it has to be clarified whether robots will become autonomous carers or whether the robot will be an assisting device for enhancing the autonomy and independence of the patient.

Lingering over the debate are also the questions about jobs. Clarity is required as to whether robots are to replace the human workforce or whether they are extending the capabilities and capacity of the workforce. For instance as the UK's population is aging a shortage of nurses is predicted.

UK robotics in a European perspective

It has been recognised by all stakeholders, including the UK Government (Willetts 2013) that the UK is lagging behind as a producer of robots as well as in applying automation and robotics. The number of robots set against the number of employees in the UK is dwarfed in comparison to Germany, Sweden and Italy (refer to Figure **6**).

On the other hand, UK robotics research is recognised internationally. The UK's share (€ 60M) in European robotics funding comes second to Germany, outperforms Italy and is three times that of France and Spain (refer to Figure **7**. However, the amount of European funding sharply contrasts with the (UK's) national £8.4M core funding for robotics.

Accelerating the up take of (currently available) robotics technology

Currently the largest (in value) market for robot applications is (automotive) industry with agriculture coming next; in both of these areas the UK is lagging behind.

A national programme paralleling the European Factories of the Future programme (FoF2020), combined or complemented with a Farm of the Future programme could provide the necessary stimuli to the UK's Industrial and Agricultural communities to catch up. Robotic technology is essential for improving productivity but also flexibility in manufacturing and other industries.

Accelerating new applications and technologies

Though, industrial robotics is the current commercial 'stronghold' for robotics, an important driver (in the Western world) for robotic developments is the pressure of the ageing populations. The latter requires robots that socially interact with humans in order to provide services. Fundamental research is required to develop the next generation of robots, and while the core technology further develops robotics is new application areas have to be explored not just by conventional roboticists but in collaboration with specialist in these areas.

Open problems

- Industrial robots has an urgent need for:
    - -- Gripping technology (vegetables, food and light weight products)
    - -- Collaborative industrial robots (humans and robots as co-workers).
- Industrial as well as mobile and service robots require:
    - Benchmarks, to compare whether one system is 'better' than the other?
    - Validation, will the robot do what it is supposed to do in particular in unpredictable environments?
    - Standardisation, allowing robots or robot parts to be easily plugged together.
- Social and care robotics:
    - Current technologies are still rudimentary and require improvement.
    - Are robots suitable and acceptable for particular tasks? Ethical and legal issues need to be addressed.
    - System for certification (robot has been judged suitable for a particular task).
- Education, robots in the curriculum:
    - Robotics requires a strong background in STEM subjects.
    - Robots in education do encourage careers in science and technology.
    - Society will become more familiar with robots: enhancing acceptance.

Common UK Approach

UK robotics research is recognised internationally for the technology *per se*, but also for the world class knowledge concerning robots collaborating with humans. However, the research is mainly European funded and results do not find their way to the UK's industry.

-National R&D program. The recommendation is for a national R&D program that focuses on a grand application to attract a wide spectrum of specialists to collaborate, which also supports SMEs to explore and develop niche markets.
A suggestion could be to set up a program along a theme such as '*Robotics in the Hospital, Care Home and Home Care of the Future*' with involvement of the NHS as end user. The internationally unique position of the NHS provides a strong incentive for standardisation and certification.

-Community building. At the European level, Robotics2020 has been launched; connecting the European Commission with an industry platform and an academic forum.

The British Automation and Robotics Association (BARA) supports the Academic Forum for Robotics (BARA-AFR). Representatives of several KTNs and recently the Robotics and Autonomous System SIG are invited to the AFR board meetings. Given that these informal relationships have already been established, a UK focussed counterpart of Robotics2020 would be relatively easy to establish.

Current Evidence Introduction:

What is a robot?

One useful image is that of a machine with some intelligence; a machine that acts in the real world by moving itself or by manipulating some other object with some degree of freedom as to what actions it can execute. Many robotic systems also include: *Sensors* and a sensor *data processing* (machine perception) unit and an encompassing *control architecture,* on top of which some sort of (in-situ) decision making will take place, often for guidance and navigation.

The word 'robot' originates from science fiction and denoted a humanlike machine that could do all a human could do, but without emotions and a conscience. Technological developments of the twentieth century such as computers and robots, have shown us is that tasks which had seemed specifically to appeal to human intelligence - such as arithmetic - can be performed better by machines (computers and calculators) while the simple things of human (and biological) life - for instance walking around in our daily environment - have proven to be very hard to recreate with a machine.

At present there does not exist a robot that can do it all, but there are robots that operate very successfully in certain restrained environments (industrial robots) or execute limited tasks in a bounded environment (vacuum cleaners). Research has shown and continues to show proof-of-concept applications for robots in a large variety of environments and a wide range of different tasks, but again no robot can do everything a human being can do.

What are the aims?

In a historic perspective robotics could be seen as the latest development in the consecutive series of mechanisation, automation and (partially) autonomous robots. The development of industrialisation thus summarises as: in the early stage mechanisation (partially) replaced animal and human muscle power while human sensing remained essential; in the next step, automation reduced the need for continuous human sensing and finally robot autonomy will transfer the need for direct human control into a monitoring role.

Successful mechanisation and in particular automation depends largely on structuring the production process and environment. Machine vision, learning and advanced control (artificial intelligence) enable robots to operate in dynamic and unstructured environments: the robot obtains autonomy. Mechanisation and early automation focused on mass production; advanced automation and robotics enable customised mass products and possibly on demand production of costumer specific goods. Whereas mechanisation and automation are restricted to industrial production, robots with (partial) autonomy also have potential to offer for the service sector. Service robots are most useful when they require little or no human control or supervision.

Industrial automation and robotics, for instance in the automotive industry, aims at fully automated production and a primary issue concerns the limitations of the technology. However in other sectors, for instance the aerospace industry, the human 'feel' and intuition (hand made) is considered essential for a high quality and reliable product. Automation and robotics applications in such sectors have to complement and assist the human workforce.

In areas where robots are to assist human beings, the quest is not just for technological perfection, but the robot also has to behave 'socially' and predictable even though the behaviour of the human might be unpredictable. Also, robots are fully equipped information and communication devices; this leads to questions concerning what the information is being used for and by whom. Moreover, robots are machines that can move around and obstruct people; this sparks questions as to who is controlling the robot's movements.

Robots and their environments

The current document follows the conventional distinction between on the one hand side *Automation* and *Industrial* robotics and on the other side *Mobile* and *Service* robotics. The further ordering roughly follows the complexity and predictability of the environment in which robots are being applied.

Industrial robots are typically applied in work cells, that is, largely static and controlled environments. Mobile and service robots are designed for unknown or partially unknown environments and have to make decisions in unforeseen situations. A more recent development is collaborative and swarm robotics, where robots work together but also at the same time cause dynamics in the environment. The very complex environments include those in which humans are present. The role of the robot may vary from just having to avoid and not disturb the humans up to robots cooperating with and alongside human beings.

The chapter Next Generation Robots will briefly look at future developments in robotics that is, at possibilities to build robots differently. Conventionally, robots are given a central controller which undertakes action planning. However, in unpredictable or complex or changing environments a plan soon becomes obsolete and the environment may also trigger contradictory decisions. On going research tries to re-create ways in which natural organisms learn and make decisions. Traditionally, robots are built from stiff materials, usually metal; stiff bodies and manipulators are easier to control, provide high precision and can be operated at high speeds. The drawbacks are limited flexibility as well being dangerous for people when in operation. Developing robots built from soft materials and using, for instance, soft muscle-like driving devices, is an active research area.

Automation and Industrial robotics:

Industry is still the key application for robotics. A typical automated production process consists of a chain of rigidly connected machines, conveyor belts, guiders and stackers. Robots, usually robot arms, have the freedom to manipulate objects in three dimensions and rotate objects and are a more flexible component. Like the human arm, robot arms can also reach into cavities and partially obstructed areas. Robots can bridge connections between machines by positioning objects with high precision. Robots are typically used to operate (handle, drill, weld, polish, machine) on individual objects but can also hold objects while other machines (or a human) operate on the objects.

Industrial robots are high precision machines; the gripping of ill-defined objects such as vegetables or food or lightweight materials (foil etc.) can be a problem and major hurdle for the application of robots across many industries. Gripping remains an issue to be researched. Gripping techniques roughly can be classified as:

- Impactive: Jaws or claws which physically grasp the object.
- Ingressive: Pins, needles or hackles which penetrate the surface of the object (used in textile, carbon and glass fibre handling)
- Astrictive: Suction forces applied to object surface (vacuum, magneto or electro adhesion)
- Contigutive : Making direct contact for adhesion to take place (such as glue, surface tension or freezing)

The gripping techniques vary considerably and choices mainly depend on the characteristics of the objects to be picked. Biomimetic approaches are being studied as well, for instance the hydraulic drive in spider legs and how insects hold to surfaces. A robot improving upon a gecko’s sticking power was created at Carnegie Mellon, in 2007.

Collaborative Robotics within the Industrial Domain

Human-centred manufacturing is one of the aims of the European Union's "Factories of the Future" (FoF2020) research programme. While robots introduce flexibility into an automated process, they cannot match the flexibility of a human worker. In some sectors, for instance the aerospace industry, the human 'feel' and intuition (*handmade*) is a quality requirement and cooperative operation between robots and people is essential to reap the benefits of an indefatigable robot while delivering hand made products.

Industrial robots usually consist of rigid bodies which move at high speeds and are dangerous for human beings. Workspaces for robots are therefore physically separated and inaccessible for human workers when in operation. Human robot collaboration requires a new setting. However, the possibilities are governed by strict international standards. The new ISO 10218 standard, published in July 2011, introduces the concept of (human-robot) collaborative operation:

- **Collaborative operation:** state in which purposely designed robots work in direct cooperation with a human within a defined workspace.
- **Collaborative workspace:** workspace within the safeguarded space of the robot work cell, where the robot and human can perform tasks simultaneously during production operation.

Ensuring absolute co-worker safety in a dynamic industrial production environment is very difficult and at present true collaborative working is only viable for very small industrial robots (Kruger et al, 2009) and (De Santis et al, 2008). Concerning safe collaboration two aspects are distinguished: internal or physical safety and behavioural safety (Hermann and Melhuish, 2012). Most of the leading industrial robot manufacturers produce systems enabled with internal or physical safety technology (‘safe move’) which interfaces the robot with some form of sensing device combined with a pre-set slow and safe speed when a human incursion occurs within its working environment. However, this is not true collaborative working. In both collaborative operation and workspace the robot must operate with very limited velocity and the actuators (arm, gripper etc.) are required to be force and torque limited.

The prevalent type of collaboration is to use the robot as an assistant which passes and holds parts for a human co-worker; the robot is stationary when the co-worker is within its workspace (Morioka and Sakakibar, 2010). This is likely to become more widely used as the technology improves but in reality it often requires physical shutters or guards between the co-worker and robot to establish a normal exclusion zone during movements of the robot, which again limits the collaboration.

The key to real collaboration lies in creating situational awareness both for the robot and the human co-worker. The robot should be able to estimate the emotional and physical state of humans (USA Robotics roadmap, 2013, p20). For the human co-worker, situational awareness requires that the human can easily understand what the robot is currently doing and can foresee what it is likely to do next. This will enable the co-worker to react intuitively while avoiding potentially dangerous interactions. This may sound trivial, but it is not; it took humans quite a long time to develop rules for motorised traffic, rules which among other things aim to create transparency and enable anticipatory behaviour for instance for pedestrians, and even so fatal mistakes are still being made. Cars have only two degrees of freedom, while robot arms have many more!

In the future, true collaborative working (or symbiotic human-robot collaboration, as it is called in Horizon2020) could be achieved within an industrial environment. This requires that the relevant legislation be adapted; however the biggest hurdle to this is likely to be co-workers' acceptance of collaborative working. There will need to be done significant work to achieve sufficient trust in the technology; the issue of trust and confidence also pertains in mobile and service robotics.

Medical Surgery

Medical Robots are usually classified as serve robots, however robots for surgery might also be looked upon as a technology beyond industrial robots. In surgical applications robots can be used for precision surgery, minimally invasive surgery, surgical assistants (additional arm) or remote surgery.
Typically the human surgeon is in full control; the technological system, including the robot, has to provide maximal information to the surgeon. Imaging and navigation systems are guiding the surgeon through the intervention; there is also great need for tactile and haptic feedback to the surgeon.
EPSRC has recently announced investments in to micro-engineering facilities at Imperial College London for the development of miniaturised robots for surgery and targeted therapy. These robots are expected to have impact on minimally invasive procedures including gastrointestinal, urological, neuro, cardiac, endovascular, paediatric, and orthopaedic surgeries EPSRC (2013).

Mobile and Service Robots

Mobile and Service Robotics is focused on applying robots in (partially) unknown environments such as agricultural applications or in military and search and rescue and also in everyday human life situations such as robotic caretaking scenarios. Autonomy in navigating unknown and dynamically changing environments (3D navigation) is a core research and R&D topic with widespread potential applications; an important next step is semantic 3D navigation (USA Robotics roadmap 2013) or 3D cognition (Kranenburg-de Lange, 201)2 where geometrical data are enriched with semantic information that is information about what objects are what, they can be used for etc..

Robot autonomy also induces questions about how humans interact with robots over which they do not have (full) control. Below we first consider robot applications where there is no interaction of the robot with humans-in-the-field and after that we discuss robots that indeed do interact with humans.

Mobile robots

An often used categorisation of mobile robots stemming from the military is that of:
-Unmanned Ground Vehicle UGV
-Unmanned Aerial Vehicles UAV
-Unmanned Surface Vehicles USV
-Unmanned Underwater Vehicles UUV
This categorisation does not distinguish between remotely (human) controlled and autonomous robots. Contrary to autonomous robots, remote controlled robots require permanent supervision of a human being.

(UGV/AGV) Autonomous ground vehicles

UGVs come in many varieties, wheeled and tracked vehicles are the most common but there are also many types of legged robots and snake robots with the latter being better suited for extreme terrains. Providing robots with autonomy is still challenging. The difficulty depends on how 'structured' the environment is. Autonomous or driverless trains and subways are already in operation for decades; the railway track provides the major basis for guidance. Driverless road vehicles are also being applied; the best known example is probably the Google driverless car, which won the 2005 DARPA Grand Challenge. In the UK, trials with driverless cars have been announced by the Department for Transport (BBC news 16 July 2013), the tests will be carried by Oxford University who are also well known for their adapted Nissan Leaf and the Wildcat (in collaboration with BAE Systems) (Newman, 2011). Though for road vehicles the layout of the road and GPS are important navigation anchors, machine vision for situation analysis (other vehicles etc) and environment recognition is a major enabler for driverless cars. For agricultural purposes autonomous tractors are already commercially available and in operation (John Deere, CaseIH). The tractors navigate on a map of the field and an additional (high precision) GPS variant.

A major problem with the driverless vehicles is the legal liability in case things go wrong. Most of the driverless systems therefore have a human supervisor on board (trains, tractors) or are permanently remotely supervised.

(UAV/UAS) Autonomous Aerial Systems

Military applications have driven the recent development of UAVs and the UK is now rapidly gaining ground in both the development and deployment of UAVs. However, UAVs are also being increasingly applied to civilian applications, including law enforcement; forest fire support; search and rescue; inspection of physical assets such as pipelines, powerlines, railways and offshore wind farms; environmental and pollution monitoring; agriculture and land use monitoring. For example, UAVs were used to inspect the Fukushima nuclear reactor site in 2011 and were deployed after Hurricane Katrina to search for survivors and survey the damaged area.

UAVs, or now more commonly Unmanned Aerial Systems, (UAS, to indicate that the ground control station and communication are an integral part) are normally classified into micro, mini and then larger scale UASs; they range from a few centimetres in size e.g. Black Hornet (BBC News, 2013) to aircraft such as the Global Hawk with a wingspan of over 35 meters. Both rotary and fixed wing UASs have been developed and are in operation; fixed wing UASs are also known as 'drones'.

The level of autonomy of UASs varies from fully remote controlled through to increasingly sophisticated systems that can make decisions for themselves. These higher levels of autonomy are the focus of current research and will allow the full potential of UASs to be realised. However, the autonomy of UASs presents major technological, social and ethical challenges. Current regulations of aircraft are based around a skilled pilot being present on board the aircraft. However, the UK is a world leader in developing both the technology and regulatory framework for the autonomous operation of UASs in civilian airspace. The Civil Aviation Authority (CAA) is developing new regulations (Civil Aviation Authority, 2012) and the ASTRAEA programme represents a £62M investment in developing UASs that can routinely and safely operate in civilian airspace.

Significant research is also underway into co-operative and swarming UASs whereby many UAS work together creating the need for approaches to task allocation and co-operative decision making. Finally, how humans interact and monitor these autonomous UASs is also the subject of significant research.

(UUV/AUV) Autonomous Underwater Vehicles

Autonomous **U**nderwater **V**ehicles (AUVs) are robot submarines, which are used to explore the world's oceans or laying and maintenance of underwater pipes and cables. Communications with the AUV are limited to using acoustics (sound) when the AUV is underwater (this typically has a range of a few km) or satellite communications (such as Iridium) can be used when the AUV is floating on the sea surface. Energy supply for the propulsion system and sensors is a challenge for AUVs. Without the supply of oxygen from the atmosphere, combustion engines are not practical: the AUV must rely on batteries. Accurate navigation is also a challenge as satellite signals (for instance GPS) don't penetrate even millimetres of sea water.

The National Oceanography Centre, with branches in Southampton and Liverpool has a focus on AUV for oceanic research, and the Ocean Systems Laboratory at Heriot-Watt are leading centres of excellence in underwater robotics.

Application domains

Search and Rescue

Robots are well suited to being applied in dangerous or hazardous situations. Robots have been applied in the Chernobyl nuclear plant after the disaster. Other examples are the QinetiQ fire fighting robot which is a remote controlled vehicle carrying a hose pipe (Qinetic, 2013) and remote controlled bomb disposal robots.

Robots are also applied in the aftermath of crises such as earthquakes, in particularly to search for victims beneath the rubble from small caveats where human beings cannot pass. A problem however is the extreme terrain, unevenness, rubble etc., which hampers the movements of the robots. Search and rescue robots are mostly remote controlled; one hurdle is remotely controlling a robot that is not directly visible (with no line of sight). Murphy and Burke (2005) report on remotely controlling a search robot: '*operators spent significantly more time gathering information about the state of the robot and the state of the environment than they did navigating the robot*'.

It is interesting to note that dogs are also used for such searches and they can be carrying cameras and other sensors to enable remote observations, refer to the Canine Augmentation System (Ryerson). Obviously dogs have much better manoeuvrability and are more intelligent than robots. However the working time span for a dog is very short (a few minutes) and they are (like humans) vulnerable to hazardous substances.

The EU project Guardians (Penders et al., 2011) developed a group of autonomous robots for in-the-field support for fire fighters. Searching in smoke is a dangerous job and even well trained fire fighters might get disoriented and become lost with fatal consequences. The project assumed that if the group of robots could overcome the navigation problems they would be welcome assistants to a human fire fighter. However, in trials it became clear that the fire fighters were by no means prepared to give up their procedural routine and the feeling of security provided by these routines. The provision of robot assistance in fire fighting operations was no mere 'technical' matter but immediately raised complex emotional issues related to human trust and confidence.

Military robotics

Military robot applications are dominated by the US with huge spending in the area (assumed to be $5Bn, see below under Overseas Robotics Initiatives). The US roadmap for robotics (USA Robotics roadmap 2013) explains the aims for military robotics, high priority is given to unmanned robotic systems, autonomy is a next goal and also manned-unmanned Teaming (collaboration) is listed.

Agricultural robots

Dairy farming has been transformed by the introduction of commercially available automatic milking systems. The robot is available 24 hours a day and the cows can decide themselves when they are ready for milking. In fact a milking robot is not a single machine and is better described as a dairy farm management environment; besides milking, the system provides each individual cow with what ever the particular animal needs: additional food supplies, food supplements or medication.

Research has supported the design of optimal systems for dairy parlours and herds with respect to animal behaviours (Halachmi et al., 2002; Automaticmilking, 2000). Robots offer the livestock farmer more freedom (Kranenburg-de Lange, 2012). The UK take-up of milking robots is low compared to for instance The Netherlands, where 2,952 farms or 16% were using a robot in 2012(Sillonbelge, 2013), refer to Figure 1.

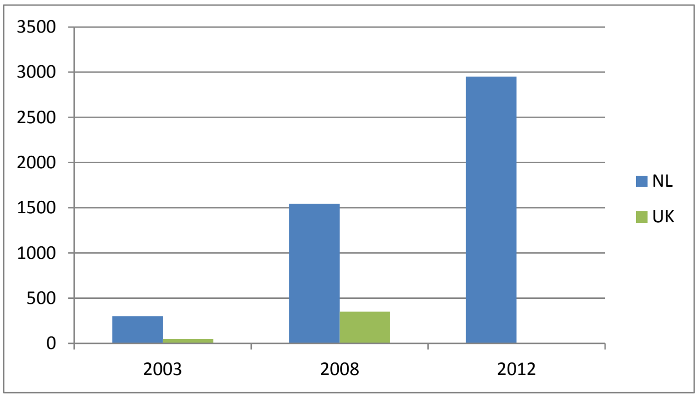

Figure 1, Number of automated milking systems operational in The Netherlands and the UK (De Boerderij 2009; Sillonbelge, 2013; Butler et al., 2012).

Arable farming is largely mechanised and robots are being introduced, for example autonomous (driverless) tractors. Mechanisation introduced blanket treatment of crops to achieve economy of scale. Autonomous robots and smart control allow scaling down treatments to plant or even leaf level. High precision spraying robots, for example, have the potential to reduce the use of plant protection products by 95% or more, as the products can be applied just at the spots where they are needed instead of spraying the whole plant or even the whole field. The future next step is (small) robots designed for individual plant care (Blackmore, 2011). They can in principle be applied in large numbers for 24 hours a day and carry out high precision but tedious tasks (such as picking or cutting individual weeds). Thus they have the potential to reintroduce or even go beyond traditional 'labour intensive' crop management tasks. In the long term, the availability of robots may revolutionise agriculture: with devices available to treat plants individually one may switch from the standard mono-cultures to mixed crop approaches.

The Netherlands is the leading country in agricultural robots, the Dutch robotics roadmap notes research in leaf picking of tomatoes, sweet pepper harvesting and packing, rose harvesting, cucumber harvesting and autonomous weed control (Kranenburg-de Lange, 2012).

Figure 2, Small robots may treat individual plants (Courtesy Harper Adams University).

Collaborative and Swarm Robotics

There is huge potential for collaborative robots, whether it is several robots working together (for instance an army of small robots weeding an arable field) or robots assisting humans. An important issue is how the collaboration is organised, options vary from a hierarchical or centralised structure (for instance master-slave, where one agent decides who is to execute which action) via multi-agent systems in which cooperation is organised using auction-like paradigms (Wooldridge 2009) up to swarm robotics, where all robots have equal status. Hierarchical structures and multi-agent systems require communication between all actors and are susceptible to communication failures. Swarm robots however act independently, they interact (but do not have to communicate) as they are competing for space or resources. The pioneering work is Reynolds's (1987) simulation of a flock of birds, but attention has in particular shifted to ants and ant colonies. Ants do not communicate but deposit markers (pheromone) and manipulate (small) objects in the environment. Other ants simply react to these markers and objects, whereby the community as a whole produces results such as nest building or carrying out raids (army ants), without there being a central controller.

Inspired by this, swarm robotics focuses on applying large numbers of simple robots. The large numbers and full decentralisation means there is no problem if some robots go missing. Application domains for large fleets include agriculture, logistics and material handling but also healthcare (USA Robotics roadmap 2013).

Swarm robotics provides robustness for unpredictable environments and faulty robots however this comes at a price. The major problems are to understand how simple rules implemented in the individual robots lead to the appropriate swarm behaviours (Penders and Alboul, 2012) and to ensure that faulty but still operating robots do not disturb the resulting behaviour of whole swarm (Bjerknes and Winfield, 2013).

Whereas the standard swarm approaches look at robots interacting with and changing their environment, another branch of swarm robotics looks at robots that connect to each other and build a larger 'organism' refer to the replicator/symbrion, projects (Liu and Winfield 2012; Replicator, 2008)

There is, as yet, no definitive answer as to how collaboration between robots is best organised. The behaviour of a hierarchical system is fully predictable but has no inherent adaptability for the unforeseen. Multi-agent systems can be self-adapting and produce variations in the order in which tasks are being executed, but basic tasks still have to be 'predefined'. Robot swarms have great potential for adaptive behaviour, but are very unpredictable.

Robots interacting with humans

European countries and Japan are feeling the pressure of the ageing populations; this is a strong incentive to develop robots that interact with humans in everyday life situations. This pressure is most strongly felt in Japan (Japan used to be a big investor in this area, see below).

Rehabilitation Robotics

Rehabilitation engineering tries to assist disabled people by providing a technological solution to everyday problems; solutions may include walkers, gloves, hearing aides, and other orthotic, mechanical, electronic, and assistive objects. *Rehabilitation robotics* aims to augment rehabilitation by applying robotic devices; besides building equipment it also includes development of robotic therapies and the use of robots as therapy aids for patients suffering from motor impairments.

Robots have been used for stroke rehabilitation for over 25 years. Langhorne et al. (2009) show promises for high-intensity repetitive task training to improve motor recovery. However, more recent studies have highlighted contradictory evidence for the high intensity training offered by robots (Lo et al., 2010) and Brochard, S., et al. (2010). Stroke rehabilitation therapies differ considerably (van Peppen et al. 2004); most therapies apply a 'holistic' approach to the patient and are not just focusing on a solution to a singular problem.

A new approach is to look at the full scenario and wider discourse of human-robot interaction in a therapeutic context. This is one of the challenges to be tackled in the SCRIPT project (FP7-ICT-2011-7-288698) (University of Hertfordshire, coordinator; University of Sheffield, partner). The project focuses on identifying types of interaction that can be therapeutic, but also playful. Patients are provided robotic gloves that support hand and finger movements. At home, patients use the glove to play an interactive game. The game helps to motivate them for further exercise, but also supports remote management of activities taking place at home.

While home-based machine mediated rehabilitation has an important economic driver, current challenges include safety of the robotic devices and their cost as well as privacy of patients during remote management. The long-term challenge to ensure widespread use of robotics for rehabilitation is to have a body of evidence supporting usefulness of robotic interventions. However, the variety of therapies, lack of standards and uniformity coupled with interventions taking place at varying stages of stroke recovery, has made it difficult to achieve a coherent body of evidence. Activities of the COST Action TD1006 European network on Robotics for neuro-rehabilitation focus on knowledge transfer at European level so that standardisation of some of the parameters would be possible in a very near future.

The common belief in the field is that correct utilisation of interactive robot technologies can benefit and influence recovery. Since this field is building up vast experience with human-robot interaction, a new generation of adaptive machinery may emerge that can be utilised by the whole of society and not remain restricted to people recovering from motor impairments or living with disabilities.

Assistive Robotics

While rehabilitation has a therapeutic focus, assistive robotics is very much concerned with living. Assistive robots have been shown to provide significant increases in the autonomy of disabled users, with an immediate impact on their quality of life, but also to have the potential to reduce the burden involved in caring for populations of disabled people in frequently under-resourced clinical settings, such as rehabilitation and residential care centres (Tapus et al 2007, Broekens et al 2009]. One application is allowing disabled people to retain their ability to navigate independently using smart wheelchairs (Soh and Demiris 2012).

An emerging challenge within the field of assistive robotics is the design of methods that can incorporate developmental aspects in the help that is provided to the patient. The fundamental point is that assistive systems should not always and unconditionally assist the patient, but attempt to balance the current needs of the patient with providing challenges that the patient can learn to overcome with assistance from the robotic system [Demiris 2009].

The aim for assistive robots that act as “intelligent tutors” shifts the focus to incorporating robots into the developmental trajectory of the patient. Principled methods to approach this task are in their infancy [Demiris, 2009]. Of fundamental importance is developing robots that approximate the patient’s current sensorimotor capabilities and challenge the patient's potential for achieving their intentions (Demiris 2007); such concepts are widespread in intelligent tutoring systems and used as potential strategies for helping (scaffolding) the user’s development.

Social robot companions

Robot companions are typically service or healthcare robots that fulfil a dual function: they are able to provide physical, cognitive or social/emotional support, and they perform these tasks in a social manner (Dautenhahn, 2007). Socially interactive robots may use a variety and combination of modalities including speech, gestures, body movements, facial expressions etc. to express social cues and regulate interactions with their users, while using planning, reasoning and machine learning methods that consider the communicative and collaborative nature of the interaction.

There are many examples of companion robots, they include robots as well as home environments. The robots can be used to handle objects, but also for cognitive support. To mention a few, the Care-O-Bot is a mobile service robot executing fetch-and-carry tasks. The CompanionAble, provides people suffering from mild cognitive impairments (MCI) with a cognitive assistive companion (Badii et al. 2009); the humanoid robot KASPAR (University of Herfordshire) serves as therapy aid for children with autism. MOBISERV is an integrated home environment for the provision of health, nutrition and mobility services, where the main interaction with the older person is via the Kompai robot (Nani et al. 2010).

The number of projects designing such robots exemplifies a growing demand for this type of assistive technology. Europe will have to deal with an aging population, moreover, in the UK, also a shortage of nurses is projected when accounting for the number of nurses nearing retirement themselves (Royal College of Nursing, 2009) and cuts to training places (Royal College of Nursing, 2012). This is prompting an increasing interest in companion robots to assist elderly users in their homes. Several companies are marketing their robots as such assistive companions, e.g. the Wakamaru robot (Mitsubishi Heavy Industries, Ltd, 2005), or the Human Support Robot (Toyota, 2012).

To become successful products that reach the market the robots have to be acceptable for their prospective users. Therefore hand-in-hand with technical research into making robots capable of assisting should go research into the user experience aspects of the technology. Exploring the older adults' perceptions, expectations and impressions of domestic robots is vital to inform the design and development of these technologies and helps to ease user acceptance.

Figure 3, KASPAR robot used to develop robot-assisted therapy applications for children with autism (Courtesy University of Hertfordshire).

Personal Robots

A personal robot relieves a person from their chores and provides a range of "life facilitating" services that one would expect from a butler, a nurse, a personal trainer, a tutor or a cook. Such multi-function robots do not exist commercially. However, a range of toys with robotic technology are appearing and disappearing on the market such as AIBO and Furby to provide "entertainment personal services". Robots that cook and serve dishes in "robot restaurants" are shown in China. The British robot "Thespian" is a humanoid robot giving entertaining interactive presentations.

A survey was conducted by Plymouth University to reveal the expectations of future users of personal robots (Bugmann & Coppleston, 2011). Many of the answers concerned domestic tasks currently conducted by humans. Personal robots appeared more as a luxury than a need. The same survey was conducted in a school for disabled students, where a number of very real needs were expressed. These included help for moving between bed and wheelchair, personal hygiene, food and drink preparation and appliances operation. We conclude that personal robots can make a real difference to the life of the disabled, by providing privacy, mobility and independence. However, the physical appearance of the robotic butler or nurse is an important issue to take into account.

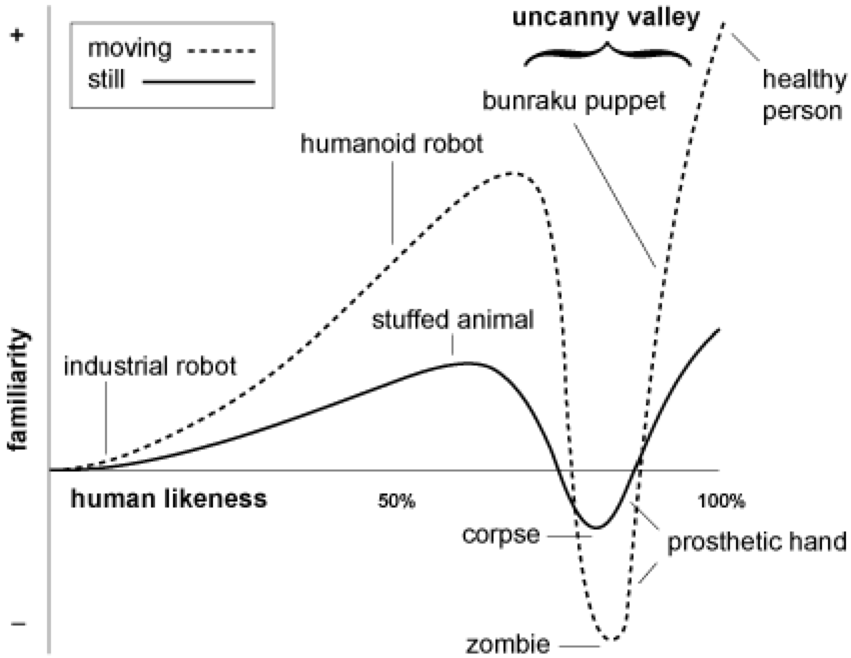

Figure 4, robot designer Mori plotted the relationship between human likeness and perceived familiarity as he saw it (MacDorman, 2005). Familiarity increases with human likeness until a point is reached at which the remaining subtle differences create an unnerving effect; movements amplify the effect. The still animal (full line) is perceived as a corpse and the humanoid robot (dashed line) as a zombie.

Humanoid robots are robots that have an appearance inspired by the human body, though they may appear quite mechanic. Androids are humanoid robots that look more humanlike. However, if a robot's appearance is very humanlike there is the danger of what the Japanese robot designer Mori called the *uncanny valley*. Mori predicted that '*as robots appear more human they seem more familiar until a point is reached at which subtle imperfections create a sensation of strangeness*' (MacDorman, 2005). The media industry is very wary of this principle in robot animations for films etc., however, the principle might apply to the real robots of the future as well. This raises questions about whether we humans really want a humanlike robot, moreover there are also related ethical questions to answer, see below.

Education Robots

Robots are expected to turn up in many facets of the human environment. However as the discussions above show, though the technology might be there, many of the applications where robots collaborate and interact with humans struggle with whether their potential users will accept robots. This is a problem to be solved by the designers, but it certainly also helps if society becomes more familiar with robots and education is a good place to start.

Robotics puts academic concepts in context (USA Robotics roadmap 2013). A wide variety of robots are used for education, either to teach robotics, or as a means to teach engineering disciplines, including computing and AI. Many teaching robots are supplied as kits or ready-built, for example Lego MindStorms, and Robotic Bioloid kits. Wheeled robots are popular as they are generally stable when built and can be made cheaply by only using two degrees of freedom. A USA survey found that students participating in a robotics program called FIRST where '*more than twice as likely to pursue a career in science and technology as non-FIRST students with similar backgrounds and academic experiences*' (USA Robotics roadmap 2013, p75).

Some institutions use home-built equipment. Plymouth University developed a humanoid robot for teaching (Wolf et al. 2009) as a means of offering students access to state of the art robotics. The robot is used to teach students the details of kinematics, real-time control of gait and computer vision guidance techniques. Students are also offered the chance to attend international robot competitions such as FIRA and Robocup.

Robots can be complex devices that can be overwhelming for students. The development of humanoid robots requires a mixture of real-time control of 20 degrees of freedom, programming vision algorithms and the building and maintenance of often fragile hardware. The use of advanced robots requires skilled staff and students with strong backgrounds in STEM subjects, the confidence to attack hard problems, and the will to give free time to the activity. At the other end of the spectrum, using simple robots is not always stimulating. Secondary-school students that are not excited by technology may not benefit from the use of robots. Some universities have been developing outreach programmes to encourage and support schools to buy Lego robotics kits, but it was observed at Plymouth that schools are often vulnerable to key teachers leaving, which can result the robotics resources being left in the cupboard.

Nevertheless, a robotic-competent workforce is essential for the competiveness of UK Plc. With a strong skill base, the UK will be well placed to take a share of the robotic market in its many forms.

Ethical Issues in robotics

As discussions above show, there are many questions about social and moral responsibility related to robotics: concerns about safety but also legal questions about liability for any errors, or damage created by robots. There is ongoing work on the legal issues raised by the increasing use of robots, although the consensus appears to be that, where possible, it is better to use existing legislation than to create special purpose laws that run the risk of being outdated by more rapid developments (Asaro, 2012). Nonetheless, there is a growing need for guidelines regarding the use of robots.

There are also concerns about job losses and deskilling where humans are replaced by robots, although the robotics industry itself creates jobs and robots need people to develop, build and maintain them. The International Federation of Robotics has published a report to show the positive impact of robotics on employment (IFR 2011). Applying more robots reduces the risk of off shoring labour to low cost countries, requires labour for new robotic products and industry expansion via product innovation and downstream jobs (*The robot report*, 30 January 2013).

There are concerns about privacy in relation to robotics because of (i) the increased possibility for surveillance and (ii) the use of robots in private spaces. Privacy issues have been raised in the context of CCTV, but mobile robots, and airborne drones extend the geographical reach of the police, the paparazzi, or just nosey neighbours to snoop in windows, or to follow individuals. In addition, as robots are welcomed into private homes further issues about privacy are involved. Robots are being developed to monitor the health and safety of elderly people, and there are important questions to be answered about who should be able to view the images and data that they have access to (Sharkey and Sharkey, 2012). Similarly, if future robots are to be used as nannies or babysitters, or as teachers, there are similar questions about who should have access to the information they store. As well as questions about who has access to their information, it is also important to consider the extent to which those who interact with such machines are aware that they are being recorded or monitored.

Additional ethical issues arise if such robots are able to direct or control people, or restrict their freedom. Many would find the use of robots to restrict or control the behaviour of people objectionable. These issues are forced further if such robots are not under the direct control of a human, but are operating autonomously. Such issues are particularly pressing in a military context, where the possibility of autonomous lethal weapons is becoming a reality, but they may also arise in domestic situations.

It has been argued that the outward appearance of robots can give rise to a particular set of ethical concerns relating to possible deception, and unrealistic expectations. For instance, humanoid robots can be developed that encourage the illusion that they are capable of understanding more than they can (Sharkey and Sharkey, 2011). However, if the robot becomes too humanlike it might loose its credibility as the *uncanny valley* thesis, discussed above, predicts.

It is possible to be optimistic about some of the developments in robotics. Robotics could, for instance, enable elderly people to live independently in their own homes for longer, for people to have better access to health care, and for transport to be made safer. At the same time, there are many ethical quandaries that need to be resolved, and pitfalls to be avoided.

Future Trends: Next Generation Robots

Control and Intelligence

Initially robots were given a central controller that would receive sensor inputs, do some reasoning and decide on an action. This type of architecture is still used for industrial robots. However, in unpredictable and changing environments more input data is required which causes an overload on the data processing unit. Moreover the data may not unequivocally support one decision.

Drawing conclusions from perception is the core aim of cognitive science and cognitive systems, for which many different solutions have been proposed. Logical systems that could do explicit reasoning were introduced early on; this is often referred to as 'formal artificial intelligence'. In the late 1980s artificial neural networks were introduced, which mimic the behaviour or neuronal cells in the brain. These networks require training and will gradually learn a solution. Contrary to the logic approaches the learned solutions remain implicit in the network structure. Training of the network can be done supervised (selecting good and bad examples) but also unsupervised, letting the devices find it out themselves usually via some sort of reward function. Genetic algorithms are applied to a group of agents and perform a quasi natural selection mechanism a 'survival of the fittest'; however, the drawback is that learning times are very long.

Cognitive science has become a discipline for its own sake; nevertheless applying cognitive systems to robotics is a lively area of research for instance at the robotics groups at the universities of Birmingham and Edinburgh.

Cognitive science has an inherent focus on drawing conclusions from an abundance of data in order to enable action selection. Contrasting approaches try to connect data collection and action selection at a low level. Several different types of robot architectures have been proposed. Behaviour based robotics (Arkin 1998) for instance roughly subdivides a robot into modules (consisting of actuators as well as sensors) each of which is specialised for a particular behaviour. Nevertheless, the problem of action selection is still not adequately solved. The integration of sensing and control directly into mechanical structures has been defined a target in Robotics2020 . Interesting in this context is for instance biomimetic robotics.

Biomimetics

Biomimetic engineering exploits design principles derived from the study of natural systems (refer to the Biokonnetwork (http://www.biokon.net/)). This approach is increasingly applied in robotics (Lepora et al. 2013) to address problems that have proved resistant to conventional engineering approaches. Biomimetic control for robots can, but need not always, take inspiration from the operation of biological nervous systems where it is often termed brain-based robotics or neurorobotics (Krichmar & Wagatsuma, 2011). Biomimetics is inspiring new robot morphologies. It is increasingly recognised that animals reduce the computational complexity of the control problems they face through elegant and efficient body designs. Biomimetics has been particularly influential in the development of artificial muscle-like actuators, insect-inspired micro-air vehicles, legged robots of various sizes and types, active sensing systems (for vision, echo-location, olfaction and touch), swimming robots, humanoid robots, and soft robots (usually based on invertebrate models).
In the UK, the Sheffield Centre for Robotics and the Bristol Robotics Laboratory have a strong focus on biomimetic and brain-based robotics; Heriot Watt and Essex Universities have developed biomimetic underwater robots, companies such as Shadow robotics and Elumotion have developed biomimetic humanoid arms and hands, and OC robotics has developed snake-like robots.

Energy

Usually the term autonomy is used to describe the ability of robots to carry out tasks without human intervention or supervision. *Energetic autonomy* refers to the ability of an agent to maintain itself in a viable energy state for prolonged periods. Different types of renewable energy sources can be exploited in environments where they are abundant e.g. solar radiation, wind force, wave power, (micro)-vibration, thermo-power. However this limits the application of the mobile robot to these particular environments or weather conditions.

Almost every environment (on earth) contains organic carbon substrates in one form or another. The biological Microbial Fuel Cell (MFC) technology can directly convert a wide range of organic matter into electricity. The technology is applicable to a wide range of wet organic matter (soluble and insoluble) e.g. sludge, lysed algal cells, insects, vegetable matter, urine and many other complex mixed substrates. This technology offers the advantages of superb longevity and low maintenance, since the microbial bio-catalyst regenerates. As most environments will contain the necessary organic fuel, applying MFC to mobile robots means that such robots could be self-sustainable (energetically autonomous) over many years.

Figure 5, EcoBot-III (Courtesy of Bristol Robotics Laboratory)

Until recently, the main disadvantage was low energy density. However miniaturisation has been shown possible and improves the energy density of individual MFCs. Furthermore, if multiples are connected as stacks, the absolute power output can be stepped up to useful levels. The data from EcoBot-III (EcoBot), the world's first practical demonstration of a self-sustainable robot (i.e. electricity translated into real work), suggest that the present energy density can be approximately 60mW/m^2. Smaller MFCs produce half the energy density but occupy only 1/6th of the volume. Therefore there is a strong argument for improving energy density through further miniaturisation.

Materials

As the discussion of applications has indicated, there is a need to develop robot technologies that match the flexibility and advanced functionality of biological muscles and sensors. A flexible body would enable a robot to pass through narrow curved passages (like a snake) or even to wriggle itself through too narrow openings

(Rossiter et al, 2006). When cooperating with humans a soft robot also seems safer than its stiff counterpart.

Muscle like actuators

Pneumatic “air muscle” actuators show good performance and are readily exploited in muscle-like configurations. Unfortunately they cannot be easily miniaturized and an air compressor is necessary (Kingsley et al, 2003). Air muscles are best suited to large scale robots operating at a fixed location so that the compressor can be co-located.

Smart materials have the potential for compact and high power density, safe and compliant actuators. Typically, smart materials exhibit a measurable response to a stimulus. Examples are: shape memory polymers which respond to temperature changes by releasing mechanical energy; shape memory alloy actuators also have good power density but are inefficient and relatively slow.
Electro-active polymers (EAPs) are also of significant interest (Carpi et al, 2010). These include a variety of different technologies that rely on electric or ionic stimulation. EAPs are particularly promising because they can produce muscle like performance but can also operate as strain or force sensors and even as energy harvesters. Many of these technologies can be fused with more conventional actuator technologies to deliver hybrid actuator technologies. Recent research at Bristol Robotics Laboratory has demonstrated that both complex multiple degrees of freedom musculoskeletal structures and micro-scale cilia structures can be replicated using soft EAP materials (Conn and Rossiter, 2012; Sareh et al, 2012).

The new field of synthetic biology is laying the foundation for bio-derived, biomimetic, and cellular functional materials and molecular and cellular robotics.

Softness and stiffness control

The ability to control the stiffness of a robot's body suits a variety of environments and tasks, and offers the potential for low-energy consuming locomotion modes such as gliding or floating. As a proof of low energy consumption, Beal et al.(2006) demonstrated that sedated fish (trout) effectively move forward against a stream of water.

EU funded projects have already made a number of advances in the theoretical and implementation aspects of soft robotics (Isuru et al.,2012). An example is granular jamming; at the University of Chicago they have created a universal gripper (Brown et al., 2010), a deformable sphere filled with ground coffee particles which stiffens in a vacuum and becomes soft again when aerated. At King’s College London, granular jamming is used to control the stiffness of a snake-like robot for minimally invasive surgery.

Research suggests (Jiang et al., 2012b) that soft robots might be ideal candidates to interact with uncertain environments; the soft and flexible bodies passively adapt (like snakes or slugs) to their environment. Soft robots or softer robots might also ease problems of robot and human collaboration. In particular, they are well suited for prosthetic assistive devices and invasive medical manipulators, since soft robots can greatly reduce the stress experienced by surrounding tissue when compared with traditional stiff robotic manipulators.

Though very promising there are several problems to be solved related to soft robots. The problems for instance concern how to estimate the pose of the robot: where are the body, head, tail, limps etc. with respect to each other. Another problem is the control of the configuration of the robot: which part of the robot acts first and how to report this back to a human operator.

Micro and Nano robotics

Micro and Nano robotics do promise new routes to inspecting, producing or treating materials and surfaces. Micro robots also find application in medical and biological domains. The Universities of Sheffield and Nothingham and Sheffield Hallam University have been active in Nano-Robotics. Slightly larger (but still small) micro robots for medical surgery are being developed at Imperial College London.

Overseas Robotics Initiatives

European Union

The Strategic Research Agenda (2014-2020) for robotics in Europe states: '*Robotics Technology will become dominant in the coming decade. It will influence every aspect of work and home. Robotics has the potential to transform lives and work practices, raise efficiency and safety levels and provide enhanced levels of service. Its impact will grow over time as will the interaction between robots and people*.' (Robotics2020, 2013).

Robotics2020 is a recently launched European Public Private Partnership (PPP) which joins together the European Commission, on the public side, and euRobotics on the private side. euRobotics is a combination of an industry platform (formerly represented by EUROP) and an academic forum (formerly represented by EURON).

The European Union's "Factories of the Future" (FoF2020) research programme (part of FP7) was launched in 2009 to address the challenges and opportunities for manufacturing (with or without Robots). The EU Horizon 2020 framework programme for Research and Innovation (which will replace FP7, starting from 2014) restates the importance of the 'Factories of the Future' program.

UK robotics in a European perspective

The number of robots applied per employee in the UK is dwarfed in comparison to data from Germany, Sweden and Italy (refer to Figure **6**). Nevertheless, UK robotics research is recognised internationally. The competition for European Union funding for research in Robotics (in FP7) is very competitive and assignment of the funding is based on comparison of the quality of proposals. The UK's share in funding comes second to Germany, outperforms Italy and is three times that of France and Spain (refer to Figure **7**).

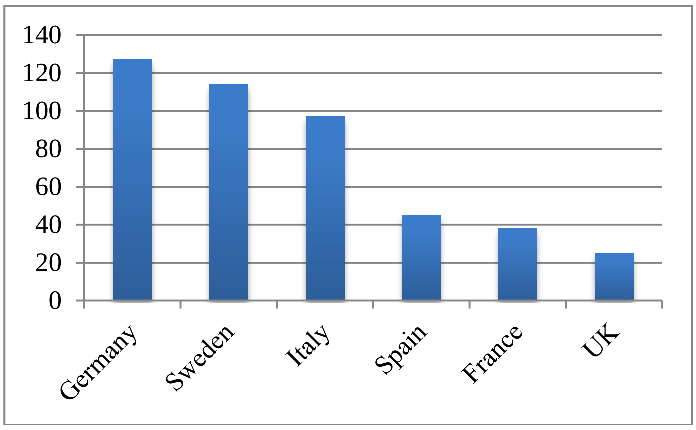

Figure 6, Robots per 10,000 employees in non-automotive sectors (International Federation of Robotics - World Robotics 2010)

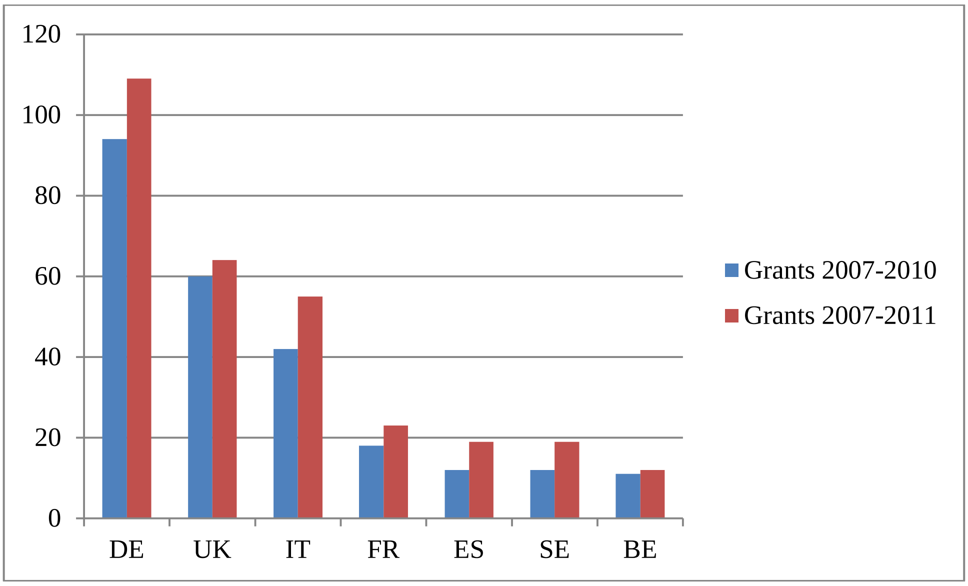

Figure 7, FP7 grants in €M by country under ICT Challenge 2: Cognition and Robotics; the UK share is around £60M..

Note: the numbers in Figure 7 do not include all EU funded robotics research; there is also robotics in, for instance, the Security calls as well as Assistive Living and the Well-being and Ageing population calls.

The € 60M of European funding for UK robotics (Figure 7) sharply contrasts with the (UK) national £8.4M core funding for robotics or the total of £25M (UK) robotics-related funding of which £14M is for Autonomous Systems (Royal Academy of Engineering, 2012). Figures to compare national robotics funding within Europe are difficult to obtain; one single case for comparison: Germany invested €30M in the Biokon network (http://www.biokon.net/), that is in a single network.

European Countries

Several European countries have dedicated government support for robotics programmes, with Germany having the largest but several others, including France and Sweden having smaller programmes. However, the most significant strategic investment in robotics in Europe is being made by the European Commission. With FP7 now closing the EC will have spent or committed €500m on the dedicated robotics and cognition programme (In total some €600m was spent by DG INFSO on robotics across their programmes). UK academic participation in this programme has been high. In addition the Factory of the Future programme spent €600m on advanced automation concept, mainly focussed on flexible automation and robotics.

With the start of Horizon 2020 in 2014, the new Public Private Partnership (PPP) in robotics has been set up with an anticipated budget in the region of €1Bn. This will focus on a roadmap driven programme aimed at increasing the commercial impact of European robotics, particularly in the service sector. Additionally, the Factories of the Future PPP is likely to be extended with a larger budget than under FP7. Its aim is to make manufacturing in Europe more competitive.

In terms of industry, Europe is the largest producer of civilian professional service robots (around 50% of world output with agriculture being the largest sector) and produces about 25% of the world's industrial robots.

USA

The largest government spend on robotics in the USA is undertaken by the Department of Defence. The annual spend on development and acquisition of robotics and autonomous systems is put by some to be well in excess of $5Bn, although this is difficult to verify. Research on service robots has until recently had little support from NSF (the main civilian funder of engineering research). However, it is evident that DARPA has spent significant sums on the support of the development of highly autonomous unmanned systems, with significant support to almost all the active robotics labs in the USA. The USA also directly supports start up and early stage robotics programmes through their SBIR and STTR (Small Business technology transfer) which effectively support early stage companies through to almost market ready production prototypes. Consequently the robotics SMEs are very vibrant in the USA, particularly in clusters around Silicon Valley, Pittsburgh and Boston.

Recently (in 2011) the Obama administration have launched the National Robotics Initiative (NRI) with a strong emphasis on "reshoring" manufacturing to the USA but also with the goal of strategically positioning robotics as a key technology for future growth. An up-dated roadmap for robotics has been published in 2013 (USA Robotics roadmap, 2013). This has been further boosted with the launch of a further manufacturing oriented initiative.

Japan

Although Japan has a reputation for leading service robotics research, it actually has a poor track record in the commercialisation of research results. This is partly structural, in that very few robotic SMEs exist in Japan and the large vertically integrated corporates require mass markets which do not yet exist. Recently research funding on robotics has been cut back with the emphasis being on certification and validation of robots designed for human cooperation and, to a lesser extent, care of the elderly. The inability of Japan to provide home developed robots to tackle the Fukushima disaster has spurred some renewed interest in robotics development but to date no significant programme has been started.

In the industrial robotics area Japan is the leading producers of systems.

South Korea

Robotics is one of the 17 strategic "growth engine" industries identified and supported by the Ministry of Knowledge Economy. South Korea is unique in the world to pass a so called "Robot Law" aimed at facilitating the development and take up of intelligent robots. Consequently South Korea is the second largest governmental funder of civilian robotics (behind only the European Commision) with an annual spend of approximately $80m. Further, South Korea has the aim to become the 3rd largest producer of industrial robots.

In industrial terms, South Korea has a thriving industry across both new SMEs and established large companies working across domestic robots, professional service robots and industrial robots. South Korea, unlike Japan, benefits from defence investment in robotics. Although hard figures do not exist, South Korea is probably the second highest provider of domestic robots (behind the USA) with most of the professional service robots currently being sold domestically.

China

China manufactures most of the world's domestic robots. It is increasingly becoming the source of Chinese designed domestic robots, particularly in the lower cost brackets. It is fair to say that China is largely in catch up mode in terms of technologies but is making headway. The large domestic market for industrial robots is increasingly being met by Chinese produced robots. Although the government funded budget for research and development is not particularly high in international terms, robotics is a key component of several programmes including the National Hi-Tech R&D Program, the Key Technologies R&D Program, and the National Basic Research Program of China. There is evidence that in certain areas the local conditions in China are favourable to them making faster progress than expected. For instance there have been more robotic brain surgery operations performed in China than in the rest of the world combined.

Conclusions and Recommendations

Accelerating the up take of (currently available) robotics technology

Currently the largest (in value) market for robot applications is industry with agriculture coming next; in both of these areas the UK is lagging behind. However, robotic technology is essential for improving productivity but also flexibility in manufacturing and other industries.
A national programme paralleling the European Factories of the Future programme (FoF2020), combined or complemented with a Farm of the Future programme could provide the necessary stimuli to the UK's Industrial and Agricultural communities to catch up.

Robots do not imply job losses (IFR, 2011); on the contrary, robots and automation:

- reduce the risk of off-shoring labour to low cost countries;
- requires labour for installation and new robotic products;
- accelerates industrial expansion via product innovation and variation;
- and in agriculture, robots create higher skilled jobs in rural communities.

Accelerating new applications and technologies

Fundamental research is required to develop the next generation of robots, such as soft robots with muscle like actuators and new control paradigms. Nevertheless, there is still huge potential in and need for further developing the 'current' robotics technology, for instance the application of current robot technology might revolutionise agriculture. Moreover, as the technologies develop further, robotics is moving on to other areas in industry and agriculture but also in medicine and health and care.

An important driver (in the Western world) for robotics is the pressure of the ageing populations which requires the development of robots that socially interact with humans. Once the technology is available markets for such robots will quickly emerge due to the societal pressure.

Currently, industrial robotics is the application and commercial 'stronghold' for robotics. Some of the hurdles for extending industrial applications are:

- gripping technology (for instance for vegetables, food and light weight industrial products);
- applying collaborative industrial robots that can become co-workers for human staff.

General hurdles for industrial as well as mobile and service robots are:

-Benchmarking, how to compare whether one system is 'better' than the other?
-Validation, what guarantees that the robotic system will do what it is supposed to do in particular in a changing and unpredictable environment?
- Standardisation, allowing robots or robot parts to be easily plugged together, for instance replace a particular robot hand with another one.

Currently, the main hurdles for social, health and care robotics are:

- the current technologies are still rudimentary and require improvement, though they do allow for trialling in everyday situations;
- the 'soft' aspects of whether robots will be suitable and acceptable for particular tasks can now be investigated but are (as yet) not fully understood;
- ethical and legal issues need to be addressed;
- certification:
  -- is the robotics device proven to support specific patient rehabilitation?
  -- is the device safe, is long term use advisible for the patient?
  -- does the assistive robot challenge the potential of the patient?
  -- does the robotics device create more freedom for the human user or is the system taking over control?
- developing suitable and acceptable robots has to involve a wide spectrum of specialists from different disciplines, but multi-disciplinary research that crosses academic boundaries is often not rewarded neither in funding nor esteem.

Standardisation

Note on standardisation: Interestingly, Willetts' eight great technologies paper (Willetts 2013) mentions Arm and Vodaphone as successful UK based companies. However these companies developed in quite different environments. Arm's first success was the BBC-Acorn computer. At the time there was no 'standard' for a PC, but soon Microsoft's operating system became a de facto standard (operating systems as Apple and Linux still being separated), with ARM having to find a particular niche for itself. Vodaphone expanded in the GSM (later UMTS etc.) market where considerable effort of the European Commission (and predecessors) had helped to generate an international standard.

Education

Concerning the issue of whether potential users will accept robots, it certainly helps if society becomes more familiar with robots and a good place to start is education. Robotics requires a strong background in STEM subjects but may also engender student interest for STEM subjects and support the teaching of these subjects. Students participating in robotics competitions are twice as likely to pursue a career in science and technology (USA Robotics roadmap 2013, p75).

Common Approach

UK robotics research is recognised internationally for the technology *per se*, but also for the world class knowledge concerning robots collaborating with humans. However, most of the UK's robotics research is European funded and results do not find their way to the UK's industry.

The recommendation is for a national program that focuses on a grand application which attracts and thus involves a wide spectrum of specialists from across many disciplines to use robotic devices. Such a program should also support SMEs to explore and develop niche markets. The lesson to be learnt from Japan - a country that did heavily invest in robotics - is that large vertically integrated corporates require mass markets which do not (yet) exist in robotics. The UK has more than 60 companies working in service robotics, mostly SMEs and university spin-outs.

A suggestion could be to set up a program along a theme like '*Robotics in the Hospital, Care Home and Home Care of the Future*'. It would be beneficial if such a thematic approach would also involve the NHS. Given the (internationally) unique position of the NHS this would also increase the chance for UK-Robotics to develop standard-setting innovations and become world leading in producing and applying this type of robotics.

Note that such a program also must include investments in the core of robotics technology (materials, mechatronics, control, sensing and machine intelligence & learning); 'soft robotics' can only thrive on top of 'hard-core' robotics.

Robotics community

Robotics2020 is a recently launched European Public Private Partnership (PPP) which joins together the European Commission, on the public side, and euRobotics on the private side. The latter is a combination of an industry platform (formerly represented by EUROP) and an academic forum (formerly represented by EURON).

The British Automation and Robotics Association (BARA) is linked to the PPMA (Processing & Packaging Machinery Association). BARA and a group of (volunteer) academics have formed the Academic Forum for Robotics (BARA-AFR). The AFR annually organises the TAROS conference which is the main UK robotics conference. Several Knowledge Transfer Networks (KTN) have special interest groups in robotics and automation; representatives of the KTNs are invited as guests to the AFR board meetings. Given that these informal relationships have already been established, a UK focussed counterpart of Robotics2020 would be relatively easy to establish.

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