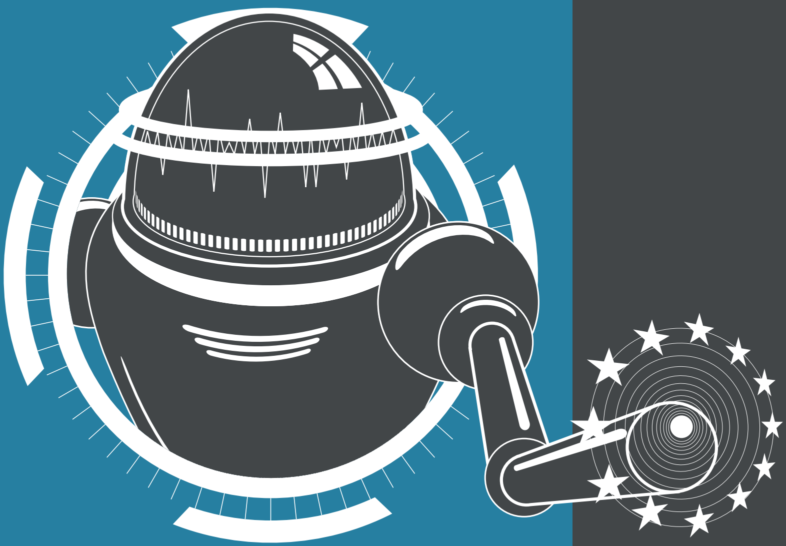
EUROP | EUROPEAN ROBOTICS TECHNOLOGY PLATFORM



ROBOTIC VISIONS

TO 2020 AND BEYOND

THE STRATEGIC RESEARCH AGENDA FOR ROBOTICS IN EUROPE, 07/2009

MISSION STATEMENT

THIS STRATEGIC AIMS ROBOTICS BUSINESS ACTIVITY

SRA

This Strategic Research Agenda (SRA) was compiled by the industry-driven Coordination Action for Robotics in Europe (CARE) with much support from industrial and academic robotics stakeholders most of which are organised in the European Robotics Technology Platform (EUROP).

CARE

The Coordination Action for Robotics in Europe (CARE) is a project funded by the European Commission (Directorate Information Society and Media) under the 6th Framework Programme (FP6-IST-045058, 01.11.2006 – 31.10.2009). The CARE partners took the role of actively driving forward the development of this SRA based on the information collected from the community.

15 CARE PARTNERS:

RESEARCH AGENDA TO PROMOTE DEVELOPMENT AND IN EUROPE

EUROP

The European Robotics Technology Platform (EUROP) is an industry-driven platform comprising the main stakeholders in robotics. Its goal is to strengthen Europe's competitiveness in robotics research and development and global markets, as well as to improve the quality of life of European citizens.

EUROP originated in October 2004, when leading European robotics organisations realised the need for a consolidated approach to European robotics, which led to the formation of EUROP as a European Technology Platform (ETP) in October 2005.

Fraunhofer IPA · iTechnic · RURobots Cognitive Science at Work · Scuola Superiore Sant'Anna di Studi Universitari e di Perfezionamento · Indra · robosoft · Scuola di Robotica · SELEX GALILEO A Finmeccanica Company

EXECUTIVE SUMMARY

LEADING EUROPEAN ROBOTICS

Europe has a globally successful industrial robotics industry with a worldwide market share of approximately 25%. Building on this position and ensuring a strong foothold in the newly emerging market sectors of domestic service, professional service, security, and space robotics are key priorities for European robotics. These goals can only be achieved by focusing all stakeholders – which include the robotics industry, robotics researchers, and private and public investors in research and development – on a common strategic vision: The Strategic Research Agenda (SRA) for Robotics in Europe. The development of this SRA was driven by industry and is backed by the commitment of the above-mentioned European stakeholders. It represents an aggregated and well-founded position that can be used to inform strategy and technical policy in Europe, and provide a strategic focus for national and regional research programmes.

This robotics strategy was achieved through extensive analysis of market developments and future opportunities. From this, a broad range of product visions were identified. These visions provide clear evidence for the viability of cross-fertilisation between the different robotics sectors and convergence of the underlying key technologies. With suitable stimulation and investment in these common technologies a broad range of robotics activities will be enabled. Key to this is the identification of first-wave technologies that will drive early markets. The current stage and future development

CONTENT

of these technologies were analysed and the ones Europe should develop and strengthen were singled out.

Robotics is likely to be a pivotal element when targeting social challenges such as the aging population, the creation and retention of high-quality, socially inclusive employment, external and internal security threats and dealing with economic disparity arising from the recent and future EU enlargements. Therefore, European society stands to benefit greatly from a leadership position of its robotics industry.

This SRA will play a vital part in achieving this goal by 2020. It will help to establish a coordinated, market-driven approach that will lead to closer collaboration both within the industry and between industry and academia. It will further focus and optimise the required investment in technology and infrastructure and the industry's success will boost knowledge based employment. Through these effects the SRA will greatly benefit the industry and Europe's citizens.

Dr. Horst J. Kayser
EUROP President, CEO KUKA AG

18.0 MILLION

ROBOTS WILL POPULATE THE WORLD IN 2011

6.5 MILLION

ROBOTS WERE IN OPERATION WORLDWIDE IN 2007

Source: World Robotics 2008. More statistics, market analysis, and forecasts can be found here: www.ifrstat.org

WHY USE A ROBOT?

Robots are known to save costs, to improve quality and work conditions, and to minimise waste of resources. With increased flexibility and ease of use, robots are at the dawn of a new era, turning them into ubiquitous helpers to improve our quality of life by delivering efficient services in our homes, offices, and public places.

Industrial robots form an essential part of the manufacturing backbone of Europe. Without the use of robotic technologies, cost-effective production, a pillar of European wealth, would not be possible in Europe because of relatively high labour costs. Furthermore, robot-based production increases product quality, improves work conditions and leads to an optimised use of resources. The miniaturisation of robotic technologies and newly developed sensing capabilities mean that these benefits are becoming applicable to an even wider range of manufacturing industries, including those with small and varying lotsizes, materials and product geometries. Robots can also be effective in areas where there are skill shortages. As an example, a McKinsey study in Germany predicts a shortage of 6 million skilled labourers by 2020, and highlights a pressing requirement for an increase of productivity.

Significant application opportunities exist in the emerging service robotics sectors, whose products will impact on our everyday lives by contributing high-value-added services and providing safer working conditions. In the fields of medical diagnosis, therapy, and rehalibiltation robot-based systems will assist health workers performing novel procedures, thereby increasing their effectiveness. The aging population will drive the application of robotic technologies that improve the quality of life and assist people to live longer and more comfortably in their own homes. Robotic technologies, such as navigation, motion control, sensing and cognition, will enable a broad range of innovations in today's products resulting, for example, in more flexible, environmentally friendly transport systems and intelligent household appliances. Eventually these technologies will reach levels of sophistication which will make possible the widespread use of intelligent robots and robotic devices able to perform a variety of tasks in homes, offices, and public places.

Driven by the increased security needs of European citizens and the higher workload resulting from extended monitoring of our everyday environments, robots already play an increasing role in the security market. Tele-operated mobile systems are now being used in a number of security applications including bomb disposal. In the future, robots will autonomously assist with the protection of offices and homes and will help secure borders or monitor the environment in both routine and emergency operations.

In space, the use of robots has become almost obligatory. Both unmanned and manned missions, be it in Earth orbit or interplanetary, will be preceded or augmented by robots. In addition, the technologies applicable to space robotics will enable a wide range of Earth-based exploration and material processing activities from automated undersea inspection to mining and mineral extraction under hazardous conditions.

ETHICAL, LEGAL, AND SOCIETAL ISSUES

Business and consumer interests and technological advancements will lead to the wide diffusion of robotic technology into our everyday lives, from collaboration in manufacturing to services in private homes, from autonomous transportation to environmental monitoring. Building an early awareness of the resulting ethical, legal, and societal (ELS) issues will allow timely legislative action and societal interaction, which will in turn support the development of new markets.

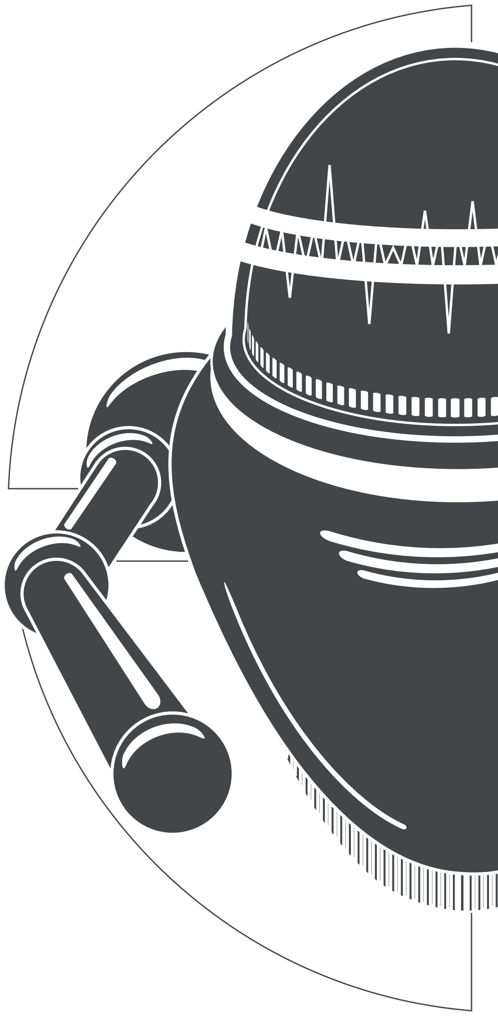
European society and many others in the world are currently facing a number of challenges including demographic and economic changes. While some of these can be met, at least partially, with robotics, doing so can have major ELS implications.

In general, the resulting issues will influence the level of acceptance of robots and robotic devices as parts of our daily lives. In some cases ELS issues can have a greater influence on the delivery of systems to market than the readiness level of the involved technologies. Existing national laws and international conventions, as well as different ethical and cultural perspectives and societal expectations across the different states of Europe need to be taken into consideration. In order for the robotics industry to become aware of these issues, cross-disciplinary education and a legal and ethical infrastructure need to be built alongside the developing industry.

The presented analysis of the ELS issues is based on the following assumptions: In the short term robots and humans will work beside each other and, in some cases, interact directly. In the mid term robots and humans will cooperate and share space with each other, both at work and at home. Robots will perform more complex tasks without constant supervision. Only in the long term will humans and robots become more integrated and will the sophistication of the interaction increase.

ETHICAL ISSUES

Wrong may be done either by the robot itself or by society when applying robotic devices. For example, robotic companions can attain a very high level of social pervasiveness. These robots will often have the ability to collect personal information and may thereby invade a user's privacy or that of bystanders. Also, robotic co-workers must be designed



such that the safety of humans and their general superior position in the control hierarchy is ensured. Particular care must be taken with the elderly and children. Robots should support, but not replace, human carers or teachers and should not imitate human form or behaviour. Further ethical issues can be derived from the European Charter of Fundamental Rights.

LEGAL ISSUES

Legal issues in robotics will mainly be related to questions of liability and responsibility. A robot may take wrong decisions as its acquired knowledge may contain inaccurate representations of the often unknown, unstructured environment surrounding it. Is the designer, producer, commissioner or user responsible for inappropriate actions of the robot? In this context, the robot's learning process needs to be controllable by those who take responsibility for the robot.

SOCIETAL ISSUES

Industrial robots already changed society. A more widespread use of robots may lead to further labour displacement and an extension of the digital divide. This may lead to the exclusion of parts of society from the benefits of advanced robotics. On the other hand, job profiles will improve as robots take over dangerous, dull and dirty jobs not only in the manufacturing industries. Finally, enhancing the human body through robotics has both positive and negative implications for the able-bodied and disabled.

Further information regarding ELS issues can be found at:
www.robotics-platform.eu/sra/els

ROADMAPPING METHODOLOGY

The developed roadmapping methodology ensures that the diversity of European robotics stakeholders stands united behind one strategic vision. The detailed analysis of potential product visions and their requirements ensures a market-driven SRA. However, opportunities originating from novel technologies were also considered.

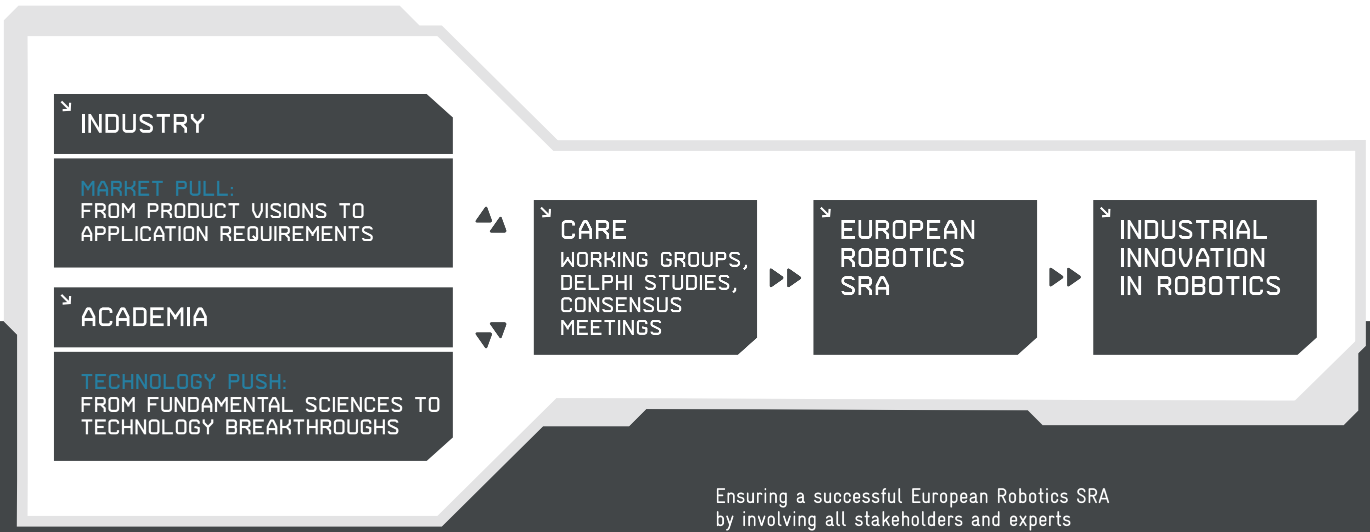
The first step in achieving a common vision is to get people to talk to each other. To ease this process, and to allow the extraction of the relevant information from this discussion, a common vocabulary was developed to provide definitions for application requirement descriptions and technologies.

MARKET PULL

To ensure a market-driven agenda, a backward or market pull analysis was used. The SRA first identified product visions in all five sectors. Careful analysis of their requirements helped to single out the technological developments required to arrive at these products. Further investigation highlighted that many product visions resulted in very similar requirements and could therefore be grouped into six application scenarios.

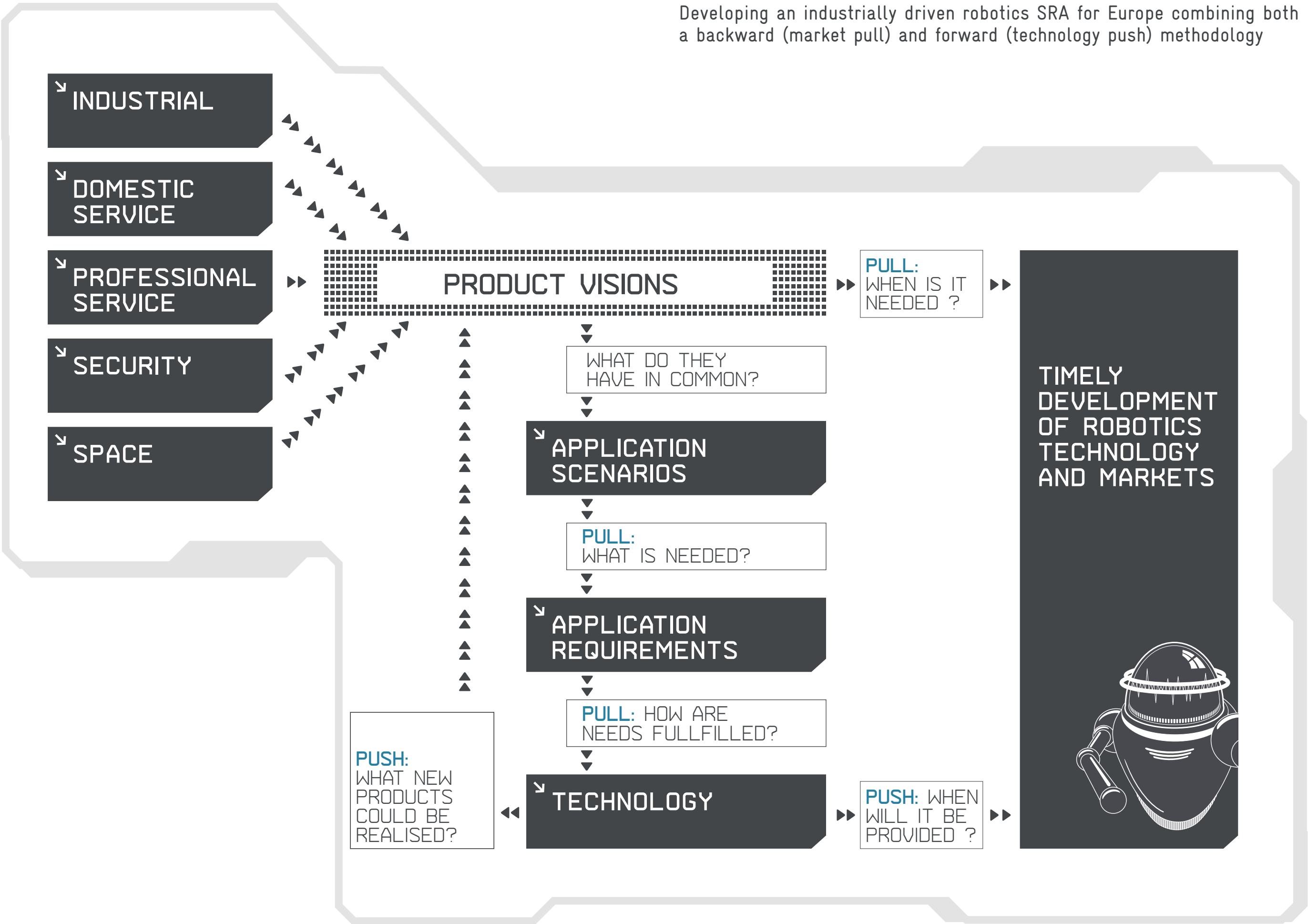
TECHNOLOGY PUSH

The backward analysis was complemented by a forward analysis or technology push approach. Here, all relevant technologies are analysed to pinpoint opportunities, which may originate from developments in research. For this the input from technology experts was sought, who were found among the scientific and industrial communities. They described the technology development status and the technological potential in the short (2010), mid (2015), and long term (2020+). In two iterations a Delphi study helped to refine and validate the technology roadmap. The technology experts were also asked to comment on the European strengths and weaknesses in these areas. Furthermore, the drivers behind the different aspects of the technology were identified. Eventually, additional product visions were identified from the resulting technology roadmap.



Ensuring a successful European Robotics SRA by involving all stakeholders and experts

Developing an industrially driven robotics SRA for Europe combining both a backward (market pull) and forward (technology push) methodology



PRIORITISING TECHNOLOGIES

Finally, the outputs of the forward and backward analyses were "fused" to form the overall picture. The aim was not to provide a holistic view of the technology world, but to prioritise those technology groups, which are more relevant for robotics and will also be mostly driven through robotics. It is important to note, however, that only with adequate progress in all technologies will the envisioned developments in robotics be achieved.

FINDING CONSENSUS BETWEEN ALL STAKEHOLDERS

The described process was facilitated by the CARE partners. A wider group of stakeholders (see pages 38 & 39) contributed to and evaluated the collected information during activities such as working group and consensus meetings, and expert consultations.

More information on our approach to roadmapping and the common vocabulary can be found at:
www.robotics-platform.eu/sra/methodology

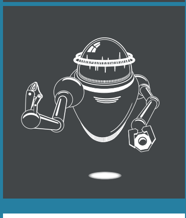
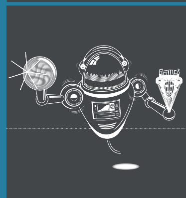
CHAPTER 02

PRODUCT VISIONS & APPLICATION SCENARIOS

More details on the application scenarios and product visions can be obtained from: **www.robotics-platform.eu/sra/scenarios**

Robots and robotic devices will have a broad impact across many existing and emerging markets, which can be grouped in the following main sectors: industrial, professional service, domestic service, security and space robotics. All product visions identified within these different sectors can be classified as belonging to one of six different, sector-overarching application scenarios (see table below). These application scenarios are described in detail on the following pages.

While each of the product visions has specific requirements, it is important to find similarities and common challenges. The sector-overarching application scenarios help in formulating these as a distinct set of application requirements (see Chapter 03). This approach also makes it possible to identify, group, and assess the key technologies required to fulfil these requirements (see Chapter 04), which in turn allows an assessment of the timely viability of future products.

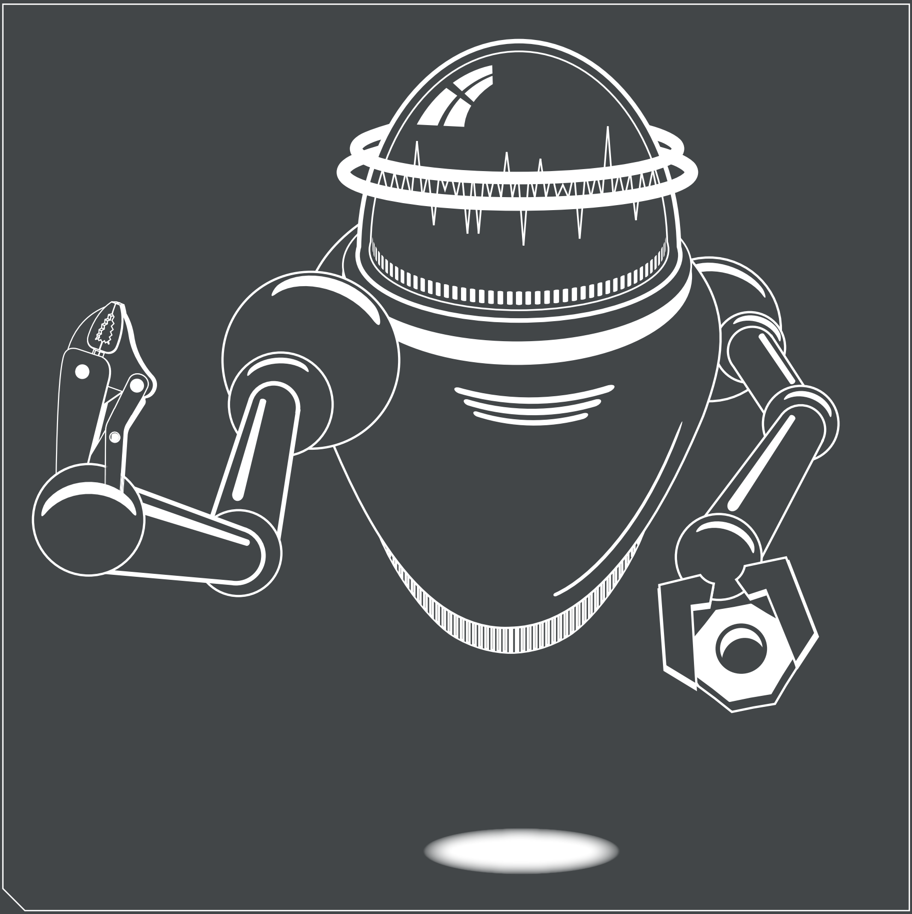
APPLICATION SCENARIOS ▶	ROBOTIC WORKERS	ROBOTIC CO-WORKERS	LOGISTICS ROBOTS	ROBOTS FOR SURVEILLANCE & INTERVENTION	ROBOTS FOR EXPLORATION & INSPECTION	EDUTAINMENT ROBOTS
SECTORS ▼						
INDUSTRIAL	■	■	■			
PROFESSIONAL SERVICE	■	■	■	■	■	■
DOMESTIC SERVICE		■	■	■		■
SECURITY		■	■	■	■	
SPACE	■	■	■		■	

ROBOTIC WORKERS

Robots performing tasks autonomously

Current robotics-based manufacturing is relatively inflexible. Typically, machines are set up and left to work for long periods of time on one specific operation. In the face of relatively high labour costs and potential shortages of skilled labourers, Europe is and will remain highly reliant on robotic workers in the industrial and professional service environments. More and more dangerous, dull, and dirty jobs will be carried out by machines that will, in the long term, result in more humane, knowledge-based job profiles. This is the only way to keep production, construction, and maintenance in Europe competitive.

In the future, robotic workers will have to cope with more complex tasks such as multi-part assembly using several arms and hands, and will have to rapidly adapt to perform different jobs, first facilitated through human intervention and later autonomously. It will become easier to program single or multiple, cooperating robots. Advances related to operating envelopes will enable robots to work on much larger structures such as boats or bridges, and on much smaller ones on the micro and nano scale.



PRODUCT VISIONS

- LARGE STRUCTURE MANUFACTURING (INCL. CIVIL ENG.)
- ROBOT WITH INTEGRATED PROCESS CONTROL
- RAPIDLY ADAPTABLE MANUFACTURING CELL
- COORDINATED MOBILE MANIPULATORS
- HUMAN-LIKE ASSEMBLY ROBOT
- ROBOT AUTOMATION FOR SMALL SCALE MANUFACTURING
- POSTPRODUCTION AUTOMATION (RECYCLING, RE-MANUFACTURING)
- MICRO-MANUFACTURING ROBOT
- MAINTENANCE ROBOT
- FORESTRY AND AGRICULTURE ROBOT
- MINING ROBOT
- PROFESSIONAL CLEANING ROBOT
- ORBITAL ROBOT AGENT
- PLANETARY ROBOT AGENT

ROBOTIC CO-WORKERS

Robots working directly with and for humans

Robots will eventually work with us or assist us under many different circumstances. Their close interaction will necessitate compatibility with us to achieve safe and dependable operation, be it at work, in public, at home, or in space. They may be tele-operated or perform individual tasks or whole sequences of tasks autonomously.

Robot co-workers will allow automation to spread to all types of manufacturing industries. In the service sector robotic co-workers will assist humans performing services useful to the well-being of humans or equipment. For example, stroke patients will receive highly sophisticated therapy in the comfort and privacy of their own home. In the security sector, robots may be used for ordnance disposal or alongside security guards as they make their rounds. In space, robot assistants will reduce the number of expensive and dangerous space walks.

PRODUCT VISIONS

ROBOT ASSISTANT IN INDUSTRIAL ENVIRONMENTS	ROBOT ASSISTANT FOR PROFESSIONALS	SURGICAL ROBOT
REHABILITATION ROBOT	PERSONAL ROBOT	ROBOT ASSISTANT FOR PHYSICALLY CHALLENGED
ROBOT ASSISTANT IN SECURITY CONTEXTS	ORBITAL ROBOT ASSISTANT	PLANETARY ROBOT ASSISTANT

LOGISTICS ROBOTS

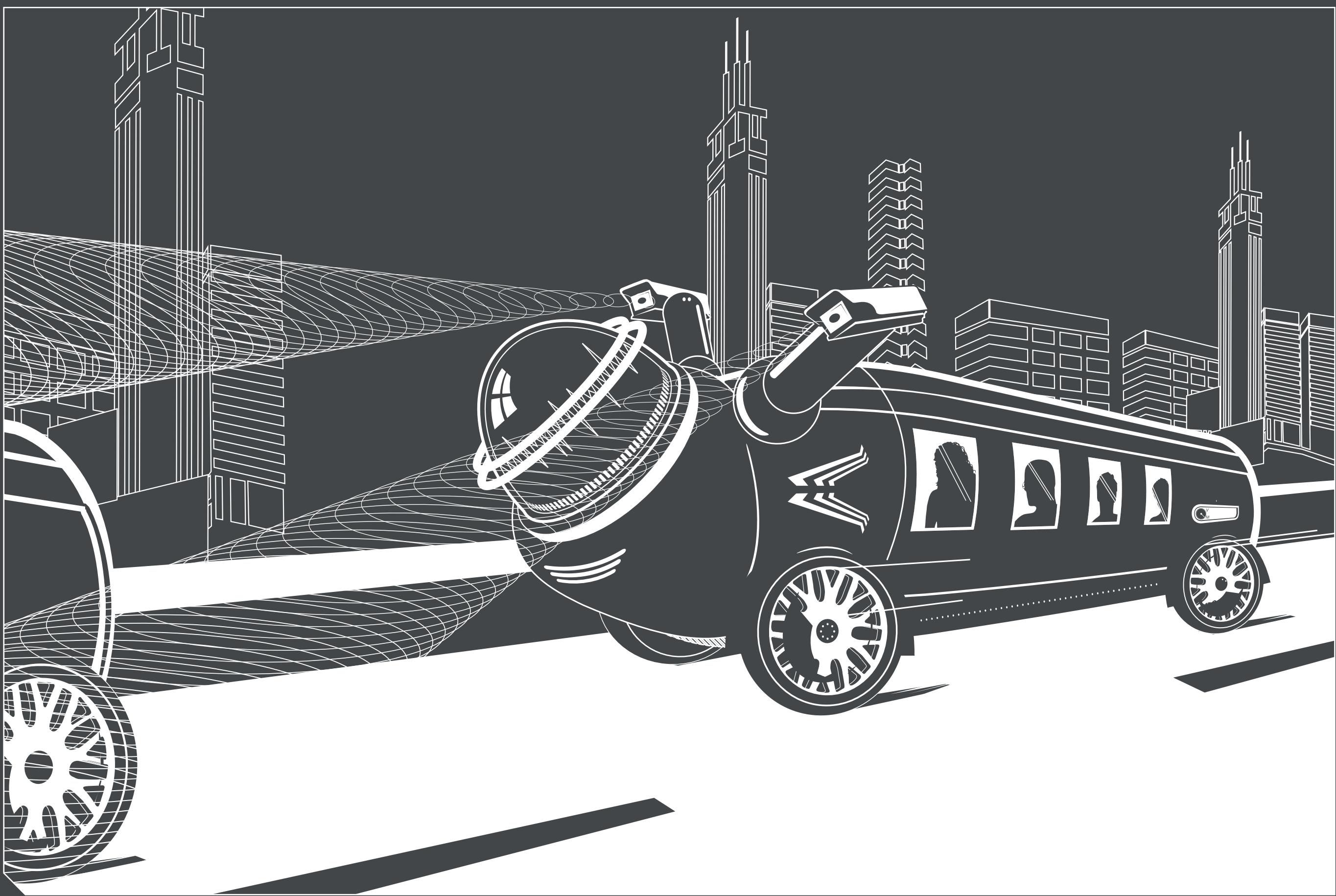
Robots moving goods and people

Logistics robots will operate in a wide variety of environments: factory warehouses, hospitals, and our existing transport networks. Already very simple forms of such robots operate, for example, as transit trains for passengers at airports. In the future their use will expand thereby providing more efficient goods management and reducing the impact of our ever increasing mobility requirements.

On the small scale logistics robots will provide transport services in hospitals, offices, and public places. On the large scale they present an opportunity to increase the efficiency of road use through the autonomous transport of people and goods. In both cases fleet management systems are needed, which collect logistics requests, dynamically assign routes and missions to the robots, manage conflicts and incidents, and schedule preventive maintenance.

PRODUCT VISIONS

- AUTONOMOUS TRANSPORT OF GOODS
- AUTONOMOUS TRANSPORT OF PEOPLE



ROBOTS FOR SURVEILLANCE & INTERVENTION

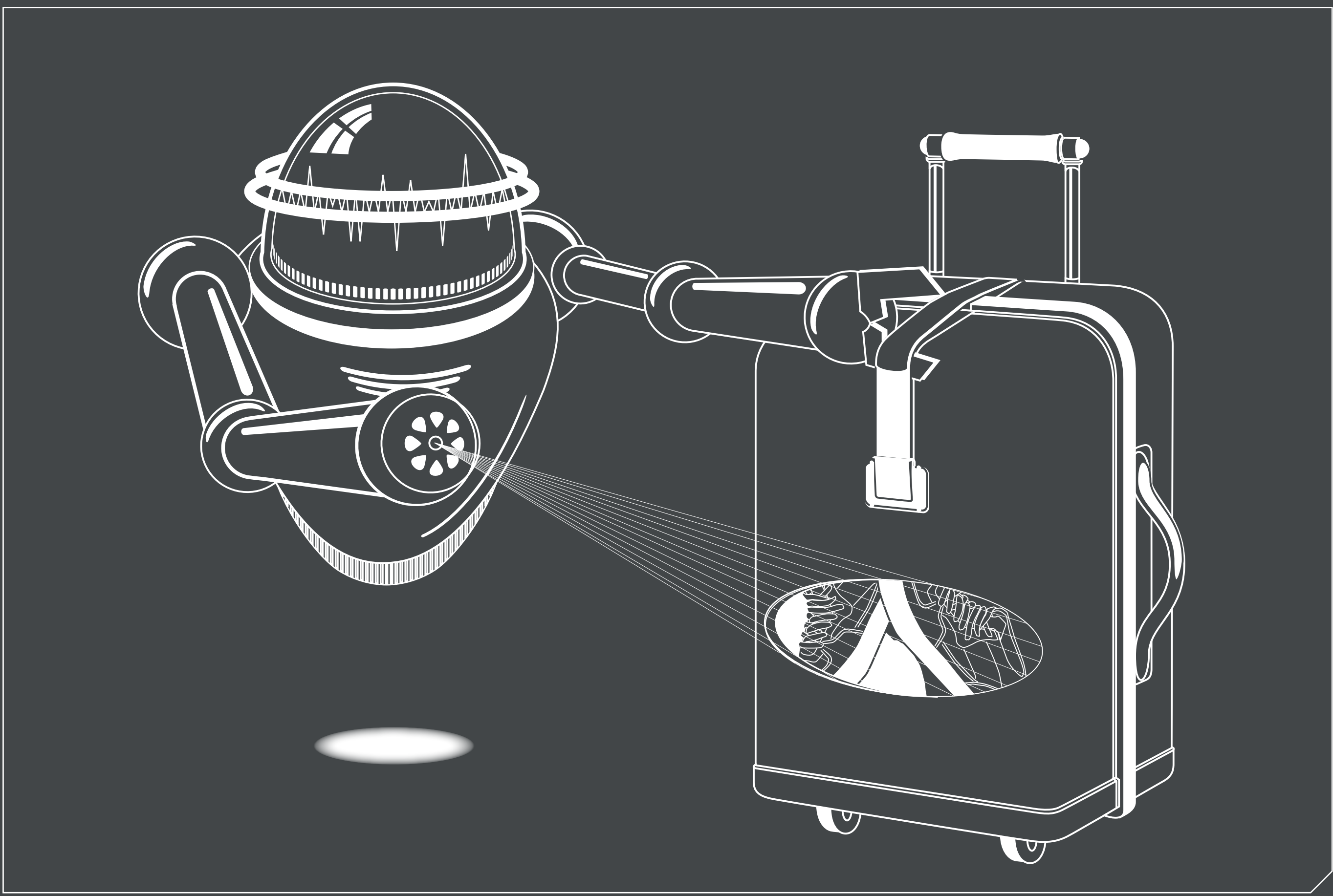
Robots protecting citizens against security threats

Surveillance and intervention robots protect homes, public buildings, industrial sites or a country's borders. They will generally work on the ground, but may also operate on or under water or in the air. These robots require some cognitive capabilities, particularly with respect to decision making, planning, and situation awareness. For the foreseeable future humans must remain in the decision loop.

Currently, their primary task is to gain information and to report back. In the mid term the use of flying robotic platforms for surveillance and monitoring will increase, in parallel with a maturation of all relevant regulations. In the long term such robots will also be able to accomplish more complex tasks such as responding to sudden and unexpected events, and identifying abnormal activities or potentially dangerous situations. Complex security missions will also increasingly require the deployment and cooperation of multiple robotic systems.

PRODUCT VISIONS

- BORDER SURVEILLANCE
- SITE PROTECTION (DOMESTIC AND PROFESSIONAL)
- SECURITY CHECKS OF GOODS AND PEOPLE



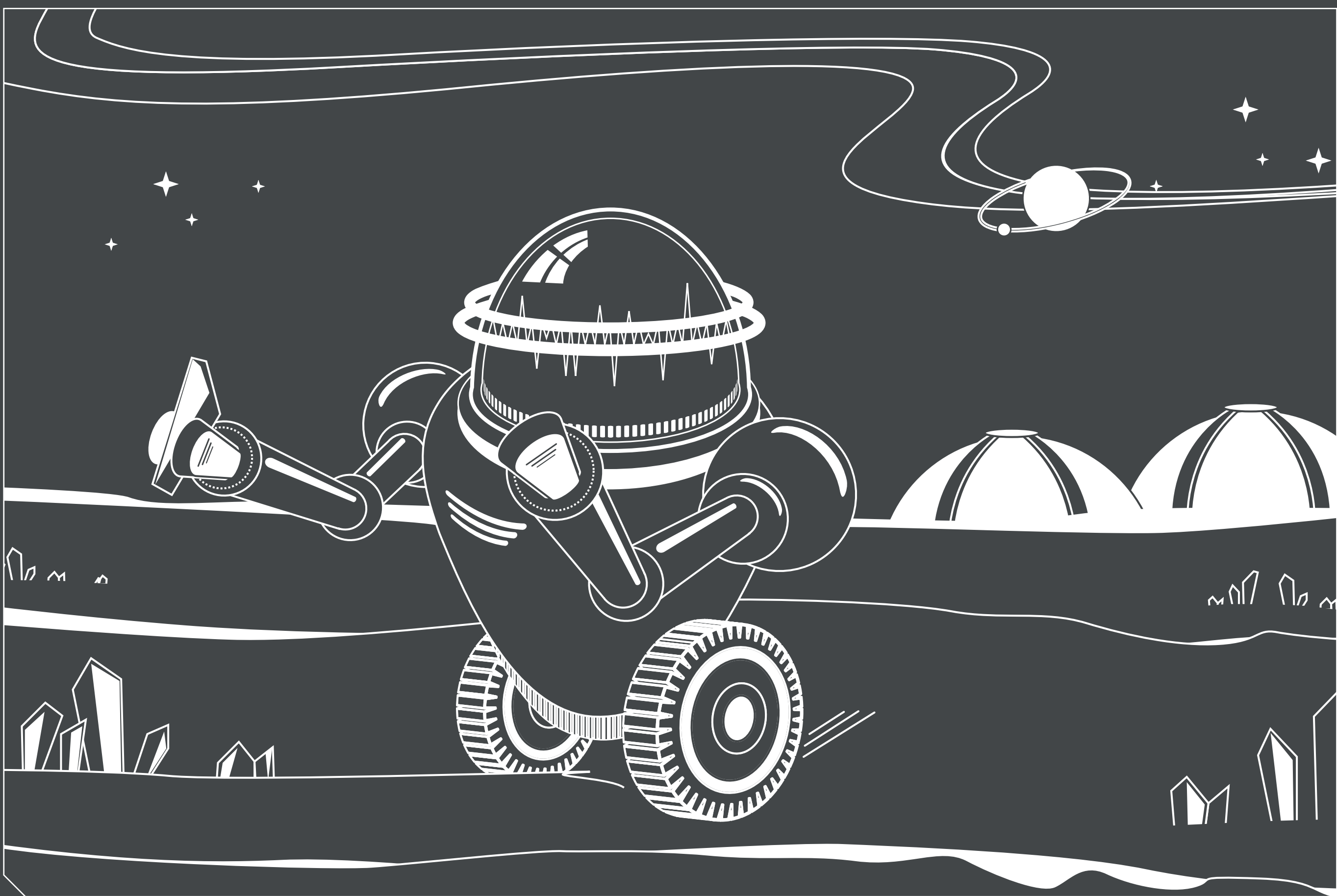
ROBOTS FOR EXPLORATION & INSPECTION

Robots in unknown or dangerous environments

Robots are ideal for operation in domains which are either inaccessible or very dangerous for people. Examples include space exploration and investigating collapsed buildings. During many missions such as the inspection of a disaster zone or the examination of an underwater pipeline reliable and faultless operation are fundamental requirements.
Currently, such robots are often tele-operated or their autonomy is restricted to a limited number of well-defined steps. In the future, higher levels of autonomy will be needed, not only in domains where communications are limited, such as space, but also to increase efficiency during time-critical operations. This may also be achieved by using multiple robots.

PRODUCT VISIONS

- INSPECTION IN ENVIRONMENTS INACCESSIBLE TO HUMANS
- UNDERWATER ROBOT
- DISASTER MANAGEMENT
- ORBITAL ROBOT EXPLORER
- PLANETARY ROBOT EXPLORER



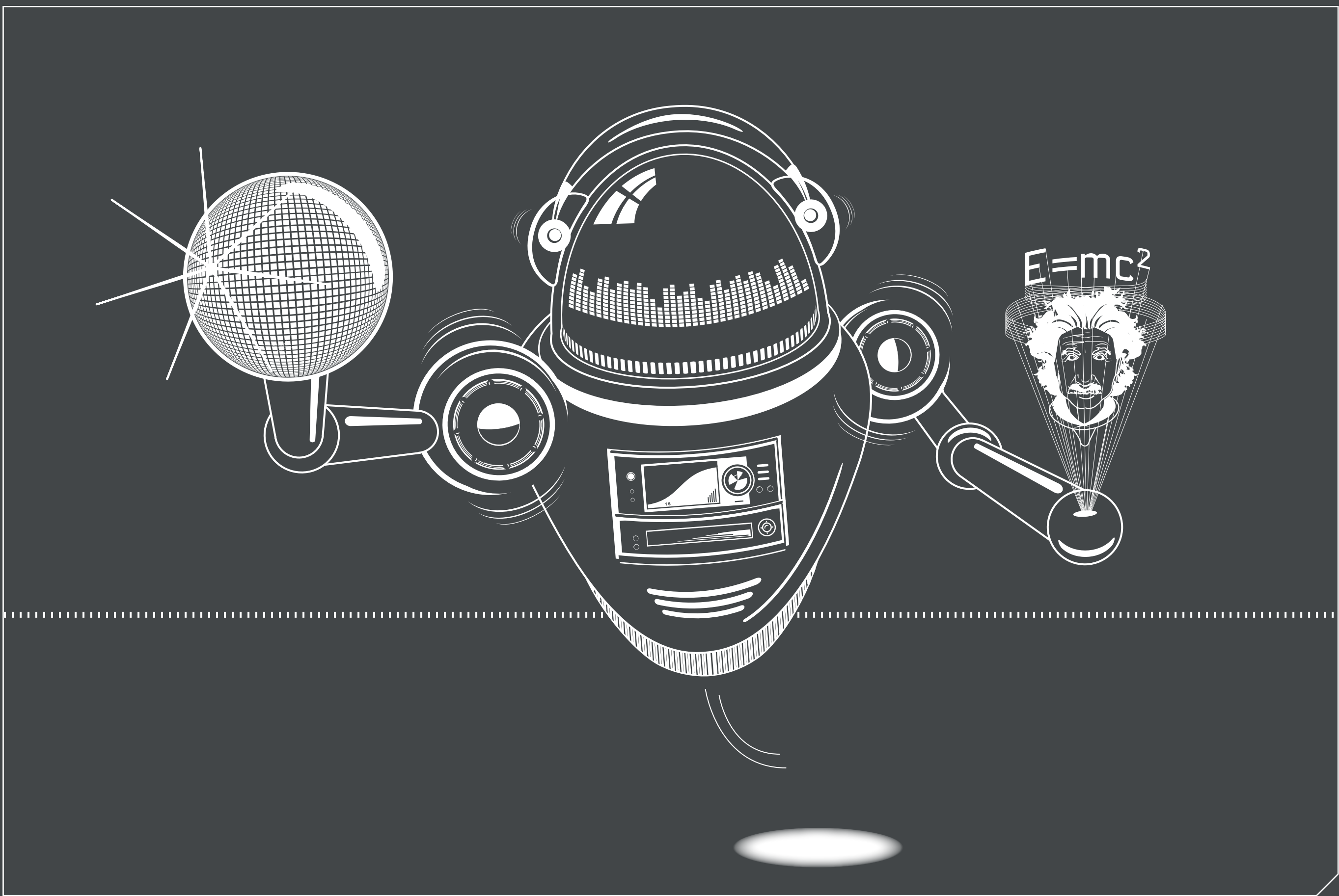
EDUTAINMENT ROBOTS

Robots educating and entertaining humans

Motion simulators, roller coasters, and educational aids, personal sports trainers or novel games – imagination is the limit. These robots will interact with humans on a cognitive and physical level. Their task may be to help educate a child, play games with them, or provide a social companion for an elderly or infirm person. Multi-modal communication including the assessment of a person's emotional state and the physical expression of emotions and gestures are of special importance in this context. Pupils, students and enthusiasts may learn much about technologies related to robotics in the process of building such systems. The main challenge in this market is to produce robots with sufficient functionality to generate novelty and fascination, and maintain the interest of a person over a significant time span at a price suitable for the mass market.

PRODUCT VISIONS

MOTION SIMULATOR	ROBOT GUIDE	ROBOT TEACHER
ROBOT TRAINER	ROBOT COMPANION	ROBOT TOY



CHAPTER 03

APPLICATION REQUIREMENTS

Detailed metrics and the timely development of the application requirements can be found at: **www.robotics-platform.eu/sra/requirements**

To turn product visions into successful products with the desired level of performance a set of requirements has to be fulfilled. Analyses undertaken as a part of the SRA development process have shown that application requirements specific to robotics can be described in terms of twelve distinct areas as introduced on the following pages.

For these application requirements detailed metrics for different product visions and application scenarios were developed. Although these have not been included here, they are available from the EUROP website. These requirements provide a technology-independent means of specifying a robot in a consistent way and are the key to identifying the relative importance of the required underlying technologies.

As any product must offer a positive price-performance ratio, cost is not considered as a separate application requirement. Developments in manufacturing technologies and the scaling effects of mass production are important in this context, but are beyond the scope of the presented work. It is, however, critical that the technology and means of production are located in or under the control of European manufacturers.

01

SUSTAINABILITY

Sustainability is a reflection of the environmental and social impact that the robot's production and its operation have. Many aspects of sustainability will be driven by regulations. In the short term these will mainly concern the production of the robot system itself. In the mid term they will also cause producers to consider the environmental impact of the operation of the robot as is already the case for white goods. In the long run, the design of a robot, including software and other aspects, will be expected to minimise the consumption of resources during the whole life cycle.

02

CONFIGURATION

Configuration is a change to the robot (or to the larger system) which is performed by the operator when the system is not in operational mode. It is done mainly through programming, instruction, initialisation, or by demonstration. Currently, configuration is carried out for a specific task or system at setup or between different tasks by online and offline programming. In the future the process of configuration will be simplified through improved user interfaces using more human-compatible modalities. Eventually, life-long adaptation will minimise the need for manual configuration.

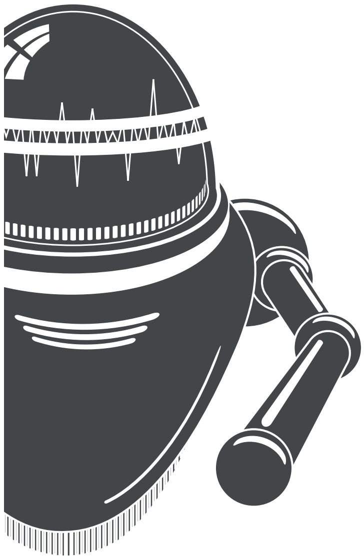
04

AUTONOMY

Autonomy is the system's ability to independently perform a task, a process or system adjustment. The level of autonomy can be assessed by defining the necessary degree of human intervention. Modern robots are mostly pre-programmed. Limited autonomy is present in some domains. In the future robot systems will perform increasingly complex (sequences of) tasks in decreasingly well-structured and known environments. Less human instruction or supervision will be needed over time. The periods covered depend on the task space and will lengthen over time.

03 ADAPTATION

Adaptation is a change to the process or the method of execution by the system itself which is generally performed at runtime. Adaptation can take place over both short and long timescales, and affect any level of the system. It may involve cognitive decision making. In the short term operational parameters of the software will be adapted to environmental changes using a database. Future robots, and later groups of robots, will adapt their hardware and software, first only to foreseen, but ultimately to more complex changes of the environment, work piece and processes.



05 POSITIONING

Positioning refers to the process of moving (the relevant parts of) the robot to a defined place. The scope of the movement can be the ground-, water- or air-bound, space or bio-environments. Today, positioning is largely based on robot and environmental models. Accuracy is achieved through well-defined mechanics and costly modifications of the environment. In the future positioning accuracy will depend increasingly on perceived environmental features. Improvements with respect to other application requirements, such as adaptation and dependability, will also lead to a better performance.

06 MANIPULATION & GRASPING

Manipulation refers to the ability to operate on an object, especially in a skilful manner. Grasping is a particular form of manipulation involving picking up and moving objects with the end effector. Nowadays, only objects with specific properties (usually rigid and known) can be manipulated. In the future the level of dexterity and strength will allow for manipulation of all kinds of objects with higher speed and precision. This will include skilful manipulation with fingers and multiple coordinated end effectors. The scale of the handled objects will range from nano to hundreds of meters.

07 ROBOT-ROBOT INTERACTION

Robot-robot interaction is the cooperation of multiple robots to achieve a common goal by carrying out the task together or by splitting it. They can interact directly or through the modification of the environment. The robots may access information gathered by teammates or from other sources. Today, cooperative tasks, which may be pre-defined or pre-scripted, are carried out by autonomous robots often under centralised control. Increasing autonomy will eventually render this unnecessary. Robots with manipulators will jointly carry out a process in close proximity. Robot teams will also cooperate.

10 DEPENDABILITY

Dependability refers to the ability of a robot to perform a task reliably, safely and with a high level of integrity. The robot itself is dependable if it is maintainable, available, robust and secure. Today, very dependable systems can be realised, but the resulting costs prevent the automation of some tasks. With time the dependability of components and the robustness of the overall systems will increase, thereby reducing the need for human intervention. Self-diagnosis and control will result in graceful degradation of the systems and thus extend the time to maintenance.

11 PHYSICAL PROPERTIES

Physical aspects describe explicit physical characteristics which are constraints for the design of robot systems. This may include the robot's shape, size or weight, or other task-specific requirements. Today, hardware is designed to meet the majority needs of large markets. With time, standardisation and modularity of components will increase and design tools will be improved. It will therefore become possible to meet more specific needs in a cost-effective manner. First, the industry will be able to serve niche markets, later those of individuals.

08 HUMAN-ROBOT INTERACTION

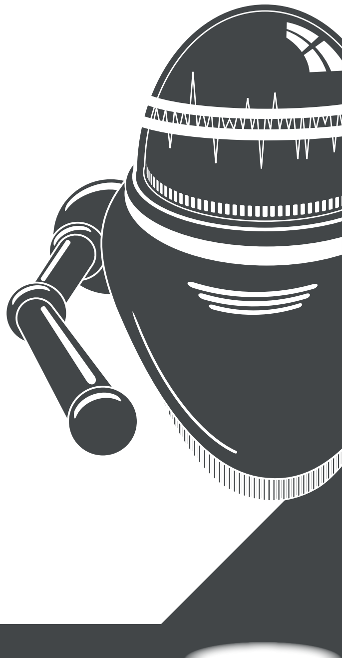
Human-robot interaction is the ability of a robot and a human to mutually communicate, which may include physical interaction. This involves communication using a common context, possibly embracing a common cognitive view. The interaction can be multi-modal using sounds, gestures, and physical interaction. They may involve or result in modifications of the environment. In the short term humans will interact with the robot using defined interfaces the human has to learn. After a series of step changes humans will naturally interact with the robot.

09 PROCESS QUALITY

Process quality describes performance quality, consistency and the success level of the robot. In some sectors this may be the level of fulfilment of the mission. The level of autonomy and the efficiency of the robot can also be factors. Today the output of robot systems is significantly superior to human performance in very specific tasks and processes and significantly worse in others. In the future, the range of tasks in which robots outperform humans is expected to significantly increase, but for the foreseeable future this will not be true across all tasks and sectors.

12 STANDARDISATION

Parts of robot systems or components that are accepted, used, or practiced by most people within the business are standardised. Software and interface standards are critical to the development of a cross-sector component industry. Benchmarking can be an important aspect of standardisation. International collaboration is essential. Currently, safety standards only exist for industrial robots and systems, but will in the future also comprise service robots. Robot components will be interchangeable and usable off the shelf. Standards for robot-robot and human-robot interaction will be developed.



CHAPTER 04

TECHNOLOGIES

More detailed descriptions and timely developments of technologies can be found here:
www.robotics-platform.eu/sra/technologies

Robotics relies on a variety of fundamental domains and is thus to a large extent the science of integrating a broad spectrum of technologies. All technologies essential to robotics have aspects that are almost exclusively relevant in the context of robotics and aspects that are relevant not only to robotics, but also to other domains. Good examples of the first, robotics-driven group are “manipulation”, “navigation”, and “perception”. Batteries provide a good example of the second group where advances will benefit robotics, but where, for now, robotics will not be a driving force.

Competitive advantages in high-technology areas are hard won. Europe must not only retain leadership where this has been achieved, but also take the lead in first-wave technologies. For Europe’s success it will be vital to capitalise on its existing strong academic base through well-managed technology transfer. However, Europe cannot afford to only concentrate on areas of strength, it will also need to foster technologies that could become critical barriers to market.

In areas of relative weakness an informed decision has to be made whether a dependence on others is acceptable. To aid these choices, an estimate of the time when technologies will be found in products is given, European strengths are highlighted and the drivers of the technologies are identified.

SYSTEM ARCHITECTURE

An architecture defines the structure of system components, their interrelationships, and the principles governing their design and evolution over time.

Robot architectures should adapt approaches from neighbouring industries (telecom, aerospace, automotive), focusing on physical human interaction. European frameworks lack popularity and reuse of components.

SHORT TERM (2010)

Hierarchical architectures running on a single system; architecture may use multiple cores for specific purposes

MID TERM (2015)

Hybrid or layered, service-oriented architectures; loosely coupled distributed modules (real-time agents)

LONG TERM (2020+)

Component compositionality & self-configuration; globally distributed, resource-aware architectures

SYSTEM ENGINEERING TOOLS

These are tools for designing a robot system (hardware and software) including simulation of its dynamic properties and deployment.

Robotics can benefit from the aerospace, automotive, manufacturing systems, games and defence industries. Europe must ensure academic skills are transferred to industry to catch up with US suppliers and open-source efforts.

SHORT TERM (2010)

Separate tools exist to aid the design of aspects of robot and application; simplistic models, which can not be linked

MID TERM (2015)

Integrated tool chain for design of robot and application (easily extendable); dynamic robot models

LONG TERM (2020+)

Integrated tool chain to custom-build robots; detailed, easy-to-use dynamic models for robot & environment

COOPERATING ROBOTS & AMBIENT INTELLIGENCE

In this field the desired collective behaviour emerges from robot-robot interactions and their interactions with the environment.

With the exception of communication and sensor networks, this area is driven by robotics. Due to its strong research community, Europe is in a good position to take leadership in the developing civilian markets.

SHORT TERM (2010)

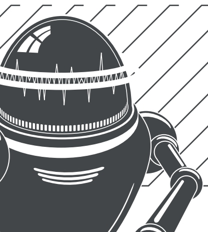
Teams of robots; centralised control and communication; tasks specified for each individual robot; use of common map

MID TERM (2015)

Distributed control; inter-agent communication; task specified for team; games & swarm theories are applied

LONG TERM (2020+)

Cooperation without explicit representation of action; skill-based or learning-based automation



(REAL-TIME) COMMUNICATION

This field is concerned with hardware and software communication within the system's time constraints in the context of its architecture.
The transfer of solutions from aerospace and the consumer electronics industry to robotics is non-trivial and has to be supported. Open frameworks for software and hardware also play an important role.

SHORT TERM (2010)

Numerous specialised protocols; Ethernet-based communication starts to take over as de-facto standard

MID TERM (2015)

New protocols using ontologies, logic, probabilistic or geometric models, rule sets, etc...

LONG TERM (2020+)

Components can figure out each others' protocols; components negotiate required quality of service

HUMAN-MACHINE INTERFACE

Interfaces enable humans and robots to communicate with each other using a variety of channels.
Human-machine and human-computer interfaces need to be extended to robotics and physical interaction. Europe's strength lies in technologies such as speech processing and haptics. Researchers should be exposed to the problems robotic designers face.

SHORT TERM (2010)

Mostly graphical or text-based interfaces; few haptic devices and use of human interaction channels; touch interfaces

MID TERM (2015)

Human interaction channels, which human has to learn; some tele-presence; haptic input devices; learning interfaces

LONG TERM (2020+)

Interaction using human channels utilising cognitive approaches; neural interfaces; non-invasive brain interfaces

SAFETY

Safety considers how to avoid or handle hazardous situations to reduce the severity and likelihood of harm to acceptable levels.
Safety methodologies from other domains must be adapted for robotic systems. Europe, based on its strong technical expertise, needs to ensure that it grows and implements its safety legislation alongside the diversifying robotic market.

SHORT TERM (2010)

Sensor-based physical safety; HW safety through redundancy; SW safety through formal approaches to programming

MID TERM (2015)

Model-based HW & SW failure detection & isolation; application safety (explosives, food, medicine, etc.)

LONG TERM (2020+)

Predictive failure detection; safe automatic obstacle avoidance; detection of the intention of a person

ACTUATION

Actuation technologies generate forces and torques to thereby manage the motion of robots.
Only specialised parts such as light-weight, compact drives and gears designed for frequent speed and direction changes are driven by robotics. While Europe has a strong foothold in drives, its dependence on others with respect to gears should be decreased.

SHORT TERM (2010)

Mostly electric, pneumatic, or hydraulic motors; light-weight high-density actuators; standard gears

MID TERM (2015)

Continuously variable transmissions; ball-socket joints; improved energy saving and power-weight ratio

LONG TERM (2020+)

High energy efficiency; safe, powerful actuators; micro actuation; use of smart materials; powerful pneumatics and hydraulics

END EFFECTORS

End effectors enable a robot to interact with and change its environment, e.g., by grasping, manipulating and processing objects.
Grippers, hands, process tools and tool changers are developed by the robotics community, but the prostheses industry is also a stakeholder. Europe is a key player in this technology area and must maintain this position.

SHORT TERM (2010)

Task-specific end effectors, esp. grippers; mostly pre-programmed or taught grasping strategies; flexibility with tool changers

MID TERM (2015)

Multi-finger grippers for a variety of objects; grasps computed online; gripping of human tools

LONG TERM (2020+)

Dexterous hands; grasping of all objects; use of multiple hands; future goal: human dexterity & assembly skills

LOCOMOTION

Locomotion allows a robot to move to a specified location on the ground, in the air, in space, on or under water, or inside a living body.
Except for biologically inspired locomotion, most aspects of locomotion are driven by other sectors. Europe is strong in biologically inspired and underwater locomotion, but lags behind in bipedal locomotion.

SHORT TERM (2010)

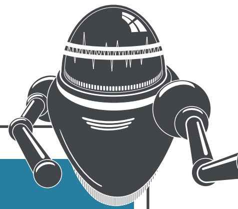
Engineering solutions to locomotion; locomotion inside the human body through external force fields

MID TERM (2015)

Biomimetic locomotion in/on water and on land; bipedal locomotion in structured environments

LONG TERM (2020+)

Bipedal locomotion in unstructured environments (mostly indoors); energy efficiency; autonomous in-body locomotion



MATERIALS

Robotic parts and systems are composed or can be made of a variety of materials. Europe is a leader in materials science and engineering. As materials R&D is mostly driven by other domains, technology transfer to robotics will be greatly beneficial, particularly in composites, light metal foams, and materials integrating functionality such as sensing and actuation.

SHORT TERM (2010)

Shape memory alloys (SMA) & electro-active polymers (EAP) for micro robots; some use of carbon/composite/metal foams

MID TERM (2015)

SMA & EAP for robot reconfiguration; biomimetic/sensing materials; some use of nanomaterials

LONG TERM (2020+)

Increased use of nano-materials; use of biomimetic materials and biological tissue; intelligent materials and structures

NAVIGATION

Navigation is concerned with controlling movement. It relies on mapping, localisation, and collision avoidance. Unlike map-based navigation, combining localisation & mapping (SLAM) and collision avoidance are robotics-driven. European strengths in navigation and motion control need to result in technology transfer, especially for outdoor navigation.

SHORT TERM (2010)

Navigation expensive (computation & sensors); localisation and mapping in controlled environments solved

MID TERM (2015)

Some perception based localisation; SLAM for challenging environments; collision avoidance considers dynamic objects

LONG TERM (2020+)

SLAM in unconstrained environments; collision avoidance with dynamic, non-cooperative obstacles through perception

PLANNING

Planning is the computation and selection of paths, motions, actions, tasks, policies, procedures, and missions for goal-directed robot behaviour.
Most aspects of planning are driven by several industries, each concentrating on their context. While Europe is strong in motion and task planning, higher level mission planning in the US is more advanced due to extensive defence and space activities.

SHORT TERM (2010)

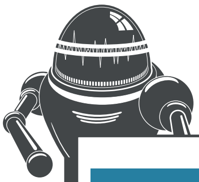
Manual programming superior to automated planning (optimised process path based on human experience); randomised motions as planning alternative

MID TERM (2015)

Automated mission and process planning using, for example, databases of expert knowledge

LONG TERM (2020+)

Autonomous, online planning for tasks of high dimensionality; learn from human (often interactively)



POWER MANAGEMENT

Power management efficiently generates, stores, and conditions power for the system.
With the exception of power management for sensors, this technology is currently driven by worldwide "e-mobility" initiatives. Europe lags behind in batteries and wireless power transmission, but excels at most other aspects including fuel cells, renewable sources, and electrical systems.

SHORT TERM (2010)

Mostly external power or local storage; regenerative brakes available, but not used often

MID TERM (2015)

Local energy conversion/generation; regeneration is standard; planners conserve energy

LONG TERM (2020+)

Efficient wireless power transfer; system efficiency continues to increase

CONTROL

Control uses algorithms and mathematics to regulate the behaviour of devices or systems.
Robotics drives the application of control theory developed in other domains to robotics (e.g., kinematics, dynamics, force control). Europe is strong in control of arms and vehicles and despite having only few players in humanoids, also in control of dynamic walking and hands.

SHORT TERM (2010)

Control through cascades; state-space controller; sliding mode controller; feedback linearisation

MID TERM (2015)

Predictive, distributed, self calibrating, self tuning controllers

LONG TERM (2020+)

Fault tolerant controllers; automatic reconfiguration of controllers

LEARNING

Learning refers to adaptation of robot behaviour through practice, experience or teaching.
Basic research on machine learning is often evaluated by robotics, but the web technology and games industries, and the AI community are also prime users. Significant public support has led to first-class research in Europe, but enhanced technology transfer is needed.

SHORT TERM (2010)

Parts of robot systems use learning methods; well-defined conditions; learning from expert teacher

MID TERM (2015)

Essential parts of controllers use learning methods; learning by experience; learning by demonstration

LONG TERM (2020+)

Complete robotic systems use learning methods (learning by observation, flexible conditions)

MODELLING

Modelling is the mathematically described approximation of reality. Most of modelling is driven by other domains, but robotics has a strong need to model and simulate the system (mechanics, actuators, electronics, and sensors) and environment at runtime. Europe is strong in modelling for control (kinematics and dynamics), biomimetics, bionics, and cybernetics.

SHORT TERM (2010)

Lack of standards for model descriptions; simulation not as good as real-world experiments; long computation times

MID TERM (2015)

Standard language for model description; interchangeable models; modelling of flexible and soft bodies; improved cybernetics

LONG TERM (2020+)

Real-time, dynamic modelling and interpretation allow for accurate assessment of the robot's and the world's state

SENSORS

A sensor detects or measures a physical quantity and converts it into electrical signals.
The development of a few sensors (e.g., skin sensors) and some sensor properties (e.g., size, weight, and safety category) are robotics-driven. Currently, economy of scale can only be achieved if the sensor is also used by other industries.

SHORT TERM (2010)

Gradual replacement of special hardware (frame grabbers, cameras...); 3D vision sensors in low resolution

MID TERM (2015)

Higher frame rate of visual sensors; greatly improved 3D vision sensors; no moving parts in laser scanners

LONG TERM (2020+)

Visual processes on sensor or dedicated processors; multi-modal sensing for intrinsic safety

SENSING & PERCEPTION

Perception is the robot's ability to build and interpret representations of the physical world from sensed data. This process may involve cognition and learning.
Sensing is not robotics-driven, but perception under real-time constraints and fusing often uncertain information from many sources are. Europe is strong in on-chip signal processing and in sensor fusion.

SHORT TERM (2010)

Sensor fusion is task-specific and relies on calibration; limited by processing power; use of attention mechanisms

MID TERM (2015)

Advanced task-dependent sensor fusion; multiple sensor modalities; step change in visual servoing; known events interpreted

LONG TERM (2020+)

Sensing on chip; perception techniques take over from fusion (closer to human perception system); no longer task-dependent

CHAPTER 05

CONCLUSIONS

The vision this SRA presents will become a reality in Europe only if the right research is undertaken, industry invests in developing products and governments create supportive frameworks. 2020 will mark a point where the major players are defined and the market will move from technology push to consumer pull. Economies of scale and continuous technology and product development will result in decreasing costs and affordable robots for European citizens. Europe's strongest competitors in this endeavour are Korea, Japan, and the US.

The supply market is likely to be shaped by agile organisations, often start-ups, owning key parts of the technology jigsaw. Early collaboration and astute intellectual property acquisition will help build viable enterprises that will in time dominate the different markets. Instrumental in enabling these collaborations will be the identification of, and the investment in, those technologies that will enable multiple new markets to grow across traditional dividing lines. One of the messages of this SRA is that the cross-sector nature of the technologies will be a defining factor in shaping the market. Ownership of key intellectual property in navigation, sensing, perception, locomotion, and manipulation can be exploited in many different markets through successful collaboration with existing stakeholders.

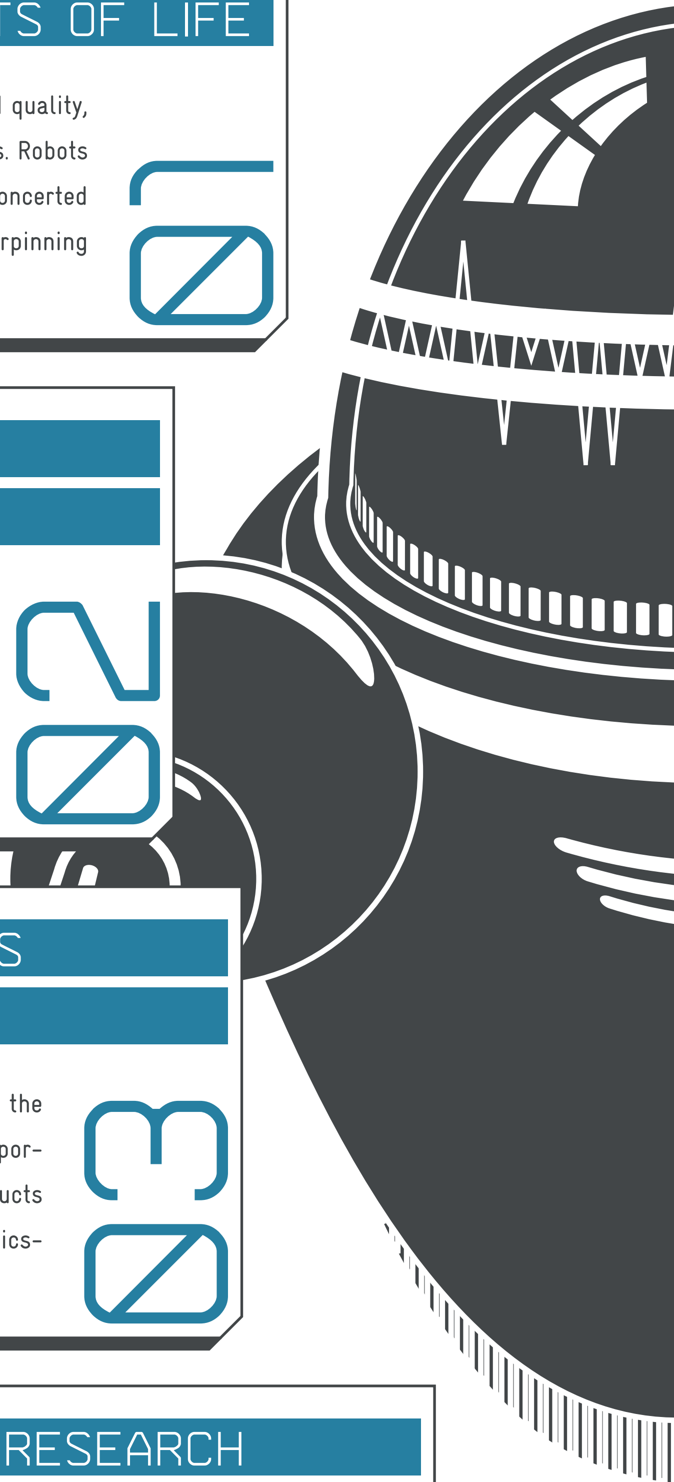
This SRA will not be judged on the detailed accuracy of its visions, but on its ability to stimulate collaboration and investment in the technology and infrastructure required to achieve a viable robotics industry in Europe in 2020.

01 TAKE ADVANTAGE OF ROBOTICS TECHNOLOGY IN ALL ASPECTS OF LIFE

In manufacturing and the crafts robots increase productivity and quality, and offer relief from strenuous and hazardous working conditions. Robots in services contribute to our quality of life and independence. Concerted European action is required to develop the technology underpinning professional and consumer products.

02 MASTER THE CHALLENGE OF SYSTEM INTEGRATION

The greatest challenge in robotics is the integration of diverse technologies from a variety of fundamental domains into one coherent system. As enablers of a broad range of innovative applications, robotics technologies will often find their way into everyday devices. The development of engineering skills, methods, and tools is crucial in this respect.



03 CREATE A EUROPEAN ROBOTICS SUPPLY CHAIN

Opportunities lie not only in the production of robots, but also in the development, supply, and integration of sub-systems – a unique opportunity for technological start-ups. As the market grows robotic products will start to influence technologies formerly driven by others. Robotics-based services will develop.

04 FOCUS ON THE RIGHT RESEARCH AND TECHNOLOGIES

Europe has a good research and technology base on which to build a globally competitive robotics industry. Japan, Korea, and the US have strengths in related areas and are investing with the aim of leadership. A head start in first-wave technologies will greatly benefit Europe, but adequate progress must be made in all areas.

AVOID ETHICAL, LEGAL, AND SOCIETAL ISSUES BECOMING BARRIERS

08

The widespread introduction of robots raises non-technical issues that may become barriers to market. Awareness must be developed at an early stage alongside the technology. Policy makers must engage with industry to create frameworks for responsible operation. Safety and ethical behaviour must be embedded into robots that make choices.

ENHANCE ROBOTICS TRAINING AND EDUCATION

07

Robotics experts and a well-trained workforce are required to research, design, develop, integrate, and support robotic products. Skill and resource shortages in the areas of engineering, control theory, physics, computer science, and cognitive science would hold back the industry. Teaching these subjects using robotics can make them more fascinating

SUPPORT CROSS-FERTILISATION TO MAXIMISE THE IMPACT OF R&D

06

Despite the many possible applications, common core technologies underlie the industry's product visions. As all sectors face similar challenges Europe's best opportunity lies with focusing on technologies that are needed across the domains. They can additionally benefit from reusing technologies from civilian and defence developments.

CREATE NEW MARKETS THROUGH SME SUPPORT AND TECHNOLOGY TRANSFER

05

Europe has a strong industrial robotics sector. Expanding this success into other domains depends on closing the gap between industry and academia through extensive technology transfer and networking. A thriving SME culture will help to spread robotics technologies into new markets and to drive the application of cognition-based technologies.

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