Strategic Research Agenda For Robotics in Europe 2014-2020

SPARC

The Partnership for Robotics in Europe

Acknowledgements

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This document and other supporting documents can be obtained from:
http://www.eurobotics-project.eu

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Who should read the SRA?

If you are a policy maker, investor, or entrepreneur trying to understand the robotics market in Europe you should read this document. It will give you an overview of the status and potential of robotics.

Depending on your interests some parts of the companion document the ***Multi-Annual Roadmap (MAR)*** , particularly those relating to innovation and products, may provide a deeper insight.

If you are an innovator, technologist or researcher you may find the detail you are looking for in the MAR document, and a higher level overview of robotics in Europe in this document.

An overview of the content of the SRA

This document provides a high level strategic overview for the robotics community. It is also intended to act as an introduction to the European robotics community for non-robotic specialists, policy makers, entrepreneurs and industries intending to use or work within the robotics market.

Its companion document ***Multi-Annual Roadmap*** is a more detailed technical guide identifying expected progress within the community and providing a detailed analysis of medium term research and innovation goals.

This SRA document has been updated from the SRA 2009 document to reflect the following factors:

- Feedback and commentary on the content of SRA 2009.
- The need to set research priorities.
- The introduction of SPARC and its effect on the goals of the SRA.
- The changes introduced in Horizon 2020.
- The need to broaden the applicability of the SRA to non-robotics organisations.

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Executive Summary

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, provide enhanced levels of service and create jobs. Its impact will grow over time as will the interaction between robots and people.

The advent of Horizon 2020 and the creation of SPARC the robotics Public Private Partnership (PPP) between the European Commission and the robotics community, represented by euRobotics aisbl, provide an opportunity to reassess the Strategic Research Agenda (SRA) published in 2009. This SRA reflects these developments, the underlying changes in the market, technical advances and the increased awareness of the potential offered by Robotics Technology.

The creation of SPARC changes the mechanisms for implementing strategy and for setting research priorities. The European Commission and euRobotics aisbl members have joint responsibility for setting and prioritising R&D&I goals. The shift in emphasis in Horizon 2020 closer to market led activities and the establishment of instruments to support this must be reflected in the strategic emphasis of the robotics community.

The Academic and Industrial communities have aligned their visions and this document, together with its companion the Multi-Annual Roadmap, represent a joint overview of the direction robotics must take in the coming decade.

The blurring of traditional sector distinctions and the creation of new technologies will alter the shape of the

market, it is important that the community embraces these changes and is ready to rise to the challenge. Technologies traditionally associated with the service robotics sector will migrate into industrial automation yielding smarter robots and open up new markets. The maturing of navigation, localisation, sensing and motion control technologies will enable economically viable service applications. Both of these trends will demonstrate the impact of robotics technology and the importance of investment, both financial and intellectual.

In order to sustain growth, investment in appropriate and targeted research is essential. This must be focused on European need and targeted where the impact will be greatest. Investment must focus on achieving step changes in performance in key technology areas such as Mechatronics, Human Robot Interaction, Systems Development and Cognition.

Europe must face the challenge of growing an innovation based community where SMEs and global companies can work together to innovate, producing robotic technology to be sold on a global scale. Achieving open innovation and creating a strong component market place are important strategic objectives.

The product visions set out here are a small sample of what might be achieved with robotics technology. The companion Multi-Annual Roadmap document provides greater detail and range in presenting visions and the technologies needed to achieve them.

Markets will encounter non-technical barriers to deployment and growth, these must be addressed with the same determination as the technical hurdles. The European strategy for robotics should align with the major societal challenges identified in Horizon 2020 and target the economic development that the European community needs. It must seek national alignment and become a key part of what Horizon 2020 delivers.

Robotics has the potential to play a part in the solution of wider societal objectives and challenges. Although robotics alone cannot solve these problems it can become a significant element in a solution to the problems posed by; an ageing population; the need to bring manufacturing back to Europe; the maintenance of our historic infrastructure; making our transport systems more efficient. While none of these major long term challenges will be solved within the timeframe of this document it points to the importance of investing in research and innovation now to create a potential future benefit.

The strategy presented in this document promotes collaboration between partners in the wider European robotics community, the stimulation of investment and the creation of an innovation climate, all of which are critical to ensuring that advances in technology are brought to market in time to increase European competitiveness and establish Europe as a global supplier in key robotic markets.

Introduction

1

SPARC Vision
What can be achieved? An outline of the Robotics Vision.

SRA Aims
An overview of the objectives of the Strategic Research Agenda.

The role of SPARC
The role and function of SPARC. Its stakeholders, its function and opportunity.

Commitment to SPARC
The commitment made by members to SPARC. Illustrating its importance in creating a cohesive community.

SPARC Vision

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, provide enhanced levels of service and create jobs. Its impact will grow over time as will the interaction between robots and people.

The technology to achieve these benefits is being developed now. Europe is in a strong position and needs to capitalise and invest, both intellectually and financially, in order to reap the long term benefit. This Strategic Research Agenda sets out a strategy backed by industry and academia to achieve these gaols.

The broad impact of robotics is such that this agenda cannot simply concentrate on research alone. It must set a path that considers the wider impact of robotics, details the necessary infrastructural development, supports innovation and creates the structures for sector growth and collaboration. Both the academic and industrial community, in conjunction with the European Commission, recognise that Europe's advantage can only be exploited by timely, appropriate and collaborative action.

There have been significant developments in both the global context and the robotics market in recent years. There have been key technical advances and, critically, the public has become more aware of robotics. All of these factors guide the focus of the SRA and the objectives of the robotics community.

Robotics has a significant role to play in the creation of jobs and the stimulation of the European economy. By lowering production costs and increasing the efficiency

of manufacturing robots it can become more profitable to produce goods within Europe. The pressing need to address strategic long-term societal issues provides a real opportunity to exploit robotic technology in key areas such as healthcare and demographic change, food security and sustainable agriculture, smart and integrated transport and secure societies.

Europe has a strong research base and industrial infrastructure from which it can innovate to exploit this fast changing landscape. In order to ensure that Europe captures this new market it must:

- Develop progressive technology, ahead of the wave.
- Exploit emergent robotics markets.
- Engage and embrace disruptive robotics technologies and systems which redefine the economics of applications.
- Instil increasing awareness in Society of the potential for robotic systems.

SRA Aims

This Strategic Research Agenda (SRA) encapsulates the collective consensus of the robotics community in Europe. It sets out objectives and provides a coordinated and definitive view of the robotics landscape.

The SRA details the strategic objectives of the robotics community and provides a focus for the aims of the robotics Public Private Partnership and its stakeholders.

The SRA sets out to achieve the following:

- To promote the objectives of the whole European robotics community.
- To highlight opportunities for research and innovation.
- To identify the current state of technology and identify future requirements.
- To introduce the European robotics community to new stakeholders.

This document is augmented by the more technically oriented Multi-Annual Roadmap (MAR) and together they constitute source documents for the call texts of robotics programmes in Horizon 2020, the eighth framework programme. The MAR will be updated annually. It identifies key technologies that should be prioritised in a European context. It overviews key markets and application areas that impact on competitiveness. It highlights innovation and research strategy and identifies alignment with key societal priorities. It identifies research opportunities and their context.

The Role of SPARC

SPARC is the agent for implementing robotics strategy within Europe. Its purpose is to connect the science base to the marketplace, a connection that ultimately benefits society. Its vision is to attain a world-wide leading position in the robotics market across all domains.

In a technology based economy the role of public bodies is to develop and implement policy that supports the creation of a viable and relevant science base, while the role of private industry is to transform the resulting technical advantage into products and services thus creating wealth and economic growth. SPARC embodies this symbiosis.

To fulfil this vision SPARC will develop strategic goals for European robotics and foster their implementation, thereby improving industrial competitiveness and industrial leadership of both European makers and, especially, users of robotics technology. A key mission in this respect will be to accelerate European robotics innovation, turning the results of research and technology development into competitive products and services at a much faster pace.

SPARC envisages that European society will benefit greatly from this leadership position; from an increased productivity, flexibility, sustainability, competitiveness and quality of manufacturing to an improved quality of life and independence of its citizens.

SPARC joins together the European Commission, on the public side, and euRobotics aisbl on the private side.

Where euRobotics aisbl represents the interests of the robotics community in Europe.

The focus of SPARC is to stimulate this interface between public and private sectors building on common interests to develop strategy, exploit robotics technologies, enable infrastructure and promote investment and innovation in turn reducing risk.

SPARC disseminates its intentions through delivery of the Strategic Research Agenda (SRA) supported by the Multi-Annual Roadmap (MAR), and the updating of these documents to reflect new developments and markets. The primary task of SPARC is to encapsulate the consensus of its stakeholders in the objectives of the SRA and ensure their implementation.

SPARC stakeholders constitute the full spectrum of interest in robotics across Europe. On one side, the European Commission and, on the other, European researchers, industry and end users. euRobotics aisbl, led by industry, having equal representation from the industrial and research communities in its executive and a wide range of members also engages with end users and interested parties through associate membership.

The goals of SPARC are to:

- Develop strategic goals for European robotics and foster their implementation.
- Improve the industrial competitiveness of Europe through innovative robotic technologies.
- Position robotics products and services as key enablers for solving Europe‘s societal challenges.
- Strengthen networking activities within the European robotics community.
- Promote European robotics.
- Reach out to new and existing users and markets.
- Contribute to policy development and address Ethical, Legal and Societal (ELS) issues.

SPARC will build on Europe’s strong position in both the industrial and service domains taking a lead role in new markets. By doing so European robotics companies will gain a competitive leadership position in world markets for both themselves and their customers.

SPARC Impact

SPARC builds on the extremely successful initiatives, underwritten by the European Commission, which have already created community effort and technical achievements that are internationally acclaimed. SPARC will be the world's largest and broadest initiative to both bring robotics into the market and to push excellence in robotics.

SPARC will bring together both industry and academia from all areas of robotics technology and application, as well as other stakeholders who are critical to the establishment of a new high-tech industry, into a single focussed body which is led, on the private side, by euRobotics AISBL.

SPARC aims to facilitate the building and empowerment of an industry and a supply chain that is capable of capturing over 42% of the world market in robotics by 2020. Even more importantly, SPARC aims to facilitate the building of value chains that will enable solutions to be quickly developed and changed as markets arise and change.

To achieve the necessary impact on markets requires a concerted action from across Europe that creates sufficient critical mass.

In this young industry SMEs are particularly important and form a vital part of the robotics landscape in terms of establishing component supply chains, driving innovation, opening up new markets and filling niches with valuable products and services. SPARC will drive entrepreneurship and SMEs. The Horizon 2020 dedicated SME instrument will be a particularly useful tool within SPARC.

SPARC will enable Europe to capitalise on its technical excellence and the skill base it has successfully created.

The expected impacts can be summarised as follows:

- A positive economic impact on the competitiveness and growth of domains deploying robotics technology.
- A positive economic impact on the competitiveness and growth of the European robotics industry.
- The creation of new jobs creation and increased job protection;
- The provision of solutions to Europe's societal challenges;
- Increasing Europe's technical excellence and skill base.

Committment to SPARC

The industrial community recognises the importance of SPARC as a necessary and progressive step in the growth of an effective and viable robotics marketplace in Europe. euRobotics AISBL and the European Commission are jointly committed to leading SPARC and ensuring that it fulfils its objectives. It recognises the strategic importance of close sustainable collaboration with academia and of engaging with the wider community of Europe to promote robotics. It welcomes the opportunity to collaborate with the European Commission in the implementation of the Strategic Research Agenda for Robotics and in effectively utilising the results of the research and innovation programmes.

The academic community similarly recognises the importance of SPARC in creating an effective and sustainable partnership with the industrial robotics community and the European Commission. It is committed to supporting SPARC and ensuring that it fulfils its objectives. It recognises the strategic importance of a close and sustainable collaboration with industry and the promotion of research and innovation strategy that is aligned with future European need. It welcomes the opportunity to collaborate with the European Commission in the implementation of the Strategic Research Agenda for Robotics by carrying out world class research and promoting innovation and technical excellence.

The members of SPARC share a common goal to make and maintain a viable and successful global robotics community within Europe.

Background

2

Why is robotics important?

What will robots do? What advantages will they have?

ELS Issues and their Impact

Ethical, Legal and Societal issues will dominate some robot markets. Responding to these important challenges is key.

Horizon 2020 and its impact

A brief introduction to the size and scale of Horizon 2020 and the role robotics will play within it.

Documentation Overview

An introduction to the different documents that compose the SRA with information about how to access them.

Why is Robotics Important?

With their increased awareness and ease of use, robots represent the dawn of a new era, ubiquitous helpers improving competitiveness and our quality of life. Robotics is set to become the driving technology underpinning a whole new generation of autonomous devices and cognitive artefacts, providing the missing link between the digital and physical worlds.

Traditional industrial robots have had a vital role in maintaining the competitiveness of European manufacturing industry. While this role will continue and widen, it is robots outside of these traditional roles that will have increasing importance and provide opportunities for rapid market growth. The significant short to medium term opportunities will be in areas such as agriculture, healthcare, security and transport while in the longer term robots will enter almost all areas of human activity including the home.

The use of industrial robots in large manufacturing companies is generally well established and understood. To expanding the market, smaller scale and SME manufacturing need to embrace smart robotics to maintain efficiency and create jobs. Raising the output and efficiency of SME manufacturers will have a significant impact on Europe's manufacturing and employment capacity. In turn this will increase overall employment as companies expand into markets considered inaccessible given Europe's comparative labour costs. Increasingly Europe will not only be competing against low wage economies but also, increasingly, highly automated ones. Leadership in robotics technology will be a key differentiator of market share in many sectors.

These smarter industrial robots draw on a much broader range of robotics technology than the systems they replace, improved human machine interfaces, the ability to learn tasks without formal programming, and higher levels of dexterity and flexibility. These technical advances directly result from research investment in Europe's academic institutions.

In the medium term robotics technology will have a far more disruptive effect on the competitiveness of non-manufacturing industries such as agriculture, transport, healthcare, security and utilities. The growth in these areas over the coming decade will be much more dramatic. From what is currently a relatively low base, service robots used in non-manufacturing areas are expected to become the largest area of global robot sales. They will have a transformational impact on a multiplicity of industries and markets.

These smart robot technologies and their integration into existing product markets will enable the exploitation of latent potential for a wide range of European manufacturers and service providers. In food security, autonomous transportation, automated farming and livestock management, and in improving healthcare delivery, and environmental monitoring. Robots have the potential to provide cost effective services, and enable the efficient delivery of high value services.

Robots provide the means to work in hazardous environments improving safety for emergency service workers, in mining and mineral extraction and in decommissioning. They can provide relentless security and will prove invaluable in civil security, border protection and the patrolling of plant and facilities. Their ability to map and monitor large spaces, under water, and from the air, will provide a new and cost effective means to gather valuable data, from the assessment of crop growth to the monitoring of environmental pollution. Thereby contributing to "big data" resources and being informed by them.

In medicine they will continue to make inroads into the provision of high accuracy surgery, and in performing repetitive procedures. They have the potential to improve outcomes in rehabilitation, and provide highly effective logistics support within hospitals.

In time they will revolutionise transport, increasing driver safety, and road efficiency. Embryonic legal infrastructures and systems are already being explored. The potential gains in the transport of goods and people are significant. Warehouses have been using robot technology for some time and these are becoming more flexible and intelligent. It is natural to extend this to the provision of warehouse to door systems and those from container to warehouse. Cutting delivery times and making cost savings that justify significant investment.

Robots will transform almost every industry and service sector, Europe has the potential to lead this process, but this requires sustained investment in research, innovation, companies, and in the infrastructure needed to integrate robotics technology within our systems and society.

ELS Issues and their Impact

European society is currently facing important challenges. Robotics can be an integral part of wider solutions to these challenges, but using them will have important ELS impacts. Addressing these impacts needs to go hand in hand with the deployment of technology.

Business interests, consumer interests and technological advancements will lead to the wide scale diffusion of robotic technology into our everyday lives. From collaborative manufacturing to providing civil security, from autonomous transportation to the provision of robot companions. Building an early awareness of the inevitable ethical, legal, and societal (ELS) issues will allow timely legislative action and societal interaction. Of equal importance is the need to ensure the designers of robot systems are aware of these issues and are provided with the guidance to create compliant and ethical systems. Addressing these important issues will help support the development of new markets by building confidence.

These issues will significantly affect the acceptance of robots and robotic devices as being an integral part of our daily lives. In some cases ELS issues will 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 will 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.

There is a growing awareness that the safeguards and enactment of standards, norms and legislation will need to be included as a part of the systems design process that creates robotic devices and technology. The modular approach to system design that is likely to become predominant will mean that the mechanisms to address ELS issues may have to be distributed through the system, rather than added on as a separate component.

The following analysis of 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 medium 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 resulting in an increasingly sophisticated interaction.

Ethical Issues

Wrong may be done either by the robot itself or by society when deploying robotic devices. For example, robotic companions may attain a very high level of social pervasiveness. They will have the ability to collect personal information and thereby invade a user's privacy or that of bystanders. 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. In all of this the designers and manufacturers of robot systems will need to engage with the issues.

Legal Issues

Legal issues in robotics relate both to issues of permittance or prohibition and also to questions of liability and responsibility. The permittance and prohibition issues relate to certain types of robots operating in particular environments or applications, e.g. self-driving cars operating on public roads. In some cases there are specific laws that define what may or may not be allowed to be undertaken but these laws often inadequately cater for robotic technology (and in particular autonomy), they often differ across national boundaries within the EC and they can become a competitive disadvantage to the development of a thriving European industry. In other cases more general laws rely on the implementation of standards, particularly safety standards, and again it is important that such standards are reviewed and updated in line with the requirements of the the emerging markets and the capabilities of the technology.

In terms of liability and responsibility a robot may make 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 the 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 have already changed society. A more widespread use of robots, despite its advantages, may lead to labour

displacement and an extensive shift in the patterns of employment. This, and other access factors such as price, 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, mundane and undesirable jobs not only in the manufacturing industries but in a broader range of tasks. Additionally, enhancing the human body through robotics has both positive and negative implications for the able-bodied and disabled. Finally robots may give capabilities to people and governments, from waging wars to automating aspects of care, which could have massive effects on the way society works and the expectations of people about their role in society.

Horizon 2020 and its Impact

Horizon 2020 is the eighth European Framework Program. It places emphasis on innovation and the transfer of technology to the marketplace.

Horizon 2020 builds on the success of the seventh Framework Program (FP7) while attaching greater importance to innovation and wealth creation resulting from research. Robotics will continue to provide a strategic focus within Horizon 2020.

Horizon 2020 has a number of strategic objectives. For the robotics community these can be distilled into the following:

- Strengthen the EU's technical and scientific position.
- Strengthen industrial leadership in innovation. This includes major investment in key technologies, greater access to capital and support for SMEs.
- Address major concerns shared by all Europeans such as; climate change, sustainable transport, affordable renewable energy, food safety and security, or coping with an ageing population.

At completion Framework 7 directly funded some 130 robotics based R&D&I projects involving around 500 organisations with total grants of some €536 million. Other funding with elements related to robotics amounts to some €170 million.

This unique level of investment has yielded a vibrant and active research community within Europe both in academia and industry. Europe therefore has a strong basis on

which to innovate and create. The focus of Horizon 2020, biased closer to the market and encompassing innovation, will help to leverage this advantage for the Robotics community as new markets and service opportunities are created.

In particular the mechanisms for pre-competitive procurement of systems and services provide an exciting opportunity to showcase the potential of robotics technology to improve service delivery and provide a real advantage.

The Horizon 2020 programme will introduce a number of specialised instruments to push innovation closer to market while at the same time stimulate dialogue between academics, producers and users of robotics technology. Most notable of these will be Pre-Commercial Procurement (PcP), and the Public Procurement of Innovation (PPI) instruments. In addition a specialised Pilot Installations instrument will be created to enable longer term deployment of robotics systems into real environments to be tested. In order to aid the involvement of SMEs in Horizon 2020 a dedicated SME instrument will be implemented that focuses on the strengths of SMEs in the Research Development and Innovation process. This is particularly critical for the Robotics community given the high density of SMEs working at the leading edge of robotics technology. The success and growth of these companies will be critical for Europe to meet its key targets.

Documentation Overview

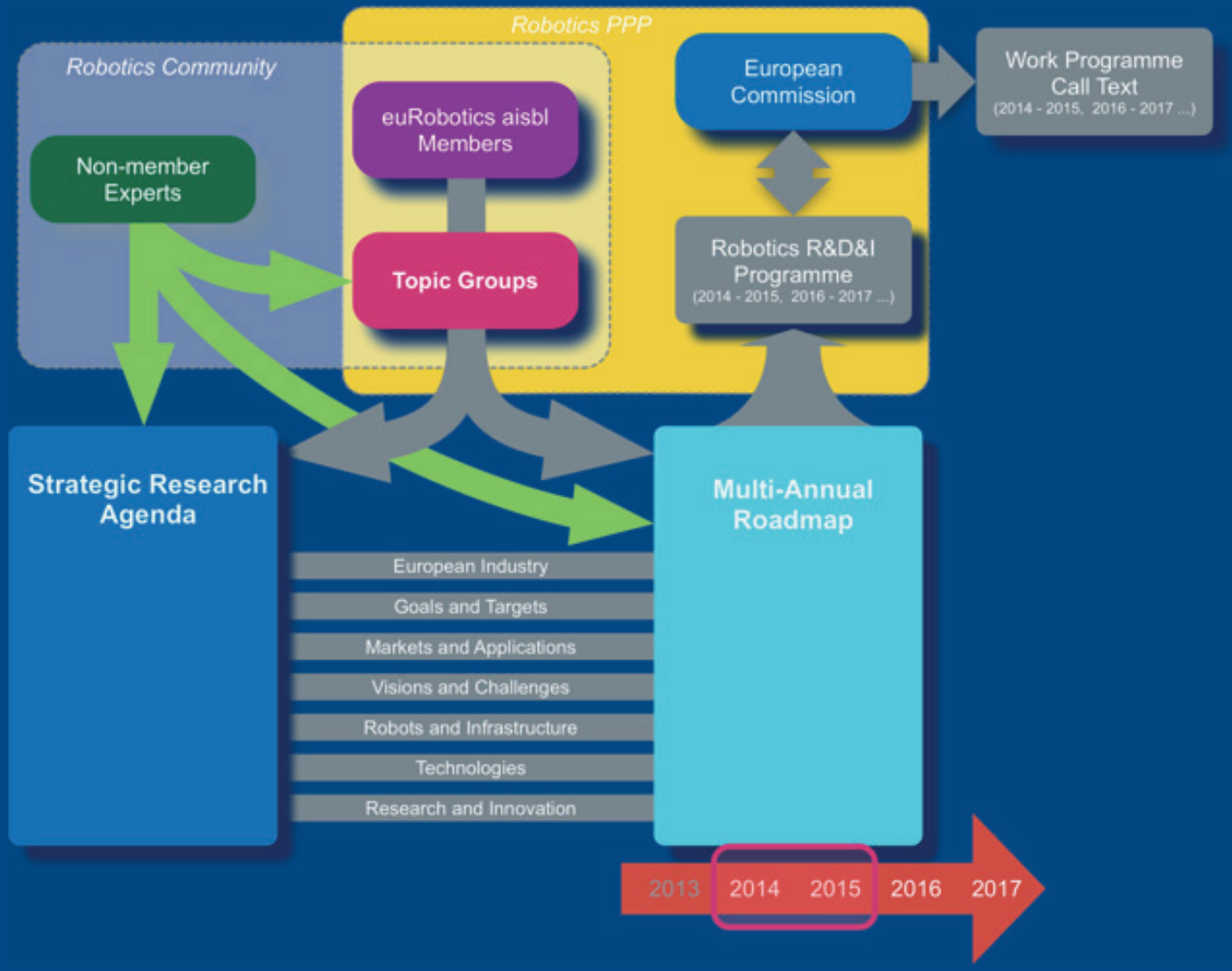
This SRA provides a coordinated and definitive view of the objectives of the robotics community in Europe. It details the strategic aims of SPARC and provides a focus for the objectives of its stakeholders.

With the creation of SPARC this Strategic Research Agenda (SRA) takes on an important role.

The SRA is divided into two distinctly different but closely related documents, this document, the *"Strategic Research Agenda for Robotics in Europe 2020"* a high level overview, and *"The European Robotics Roadmap 2020",* a technically detailed resource that will be revised annually and is referred to in this document as the Multi-Annual Roadmap (MAR). The relevance of each part to the reader will depend on their perspective.

The roadmap provides both detailed technical assessments of the state of the art and expected technical progression, as well as insights into application domains and innovation strategy. The roadmap is available on-line and in overview documents available from www.eurobotics-project.eu.

The Multi-Annual Roadmap relies on contributions from the European robotics community at each annual cycle to ensure that it is an accurate and timely reflection of current knowledge and trends.


Robotics PPP
Robotics Community
Non-member Experts
euRobotics aisbl Members
Topic Groups
European Commission
Work Programme Call Text
(2014 - 2015, 2016 - 2017 ...)
Robotics R&D&I Programme
(2014 - 2015, 2016 - 2017 ...)
Strategic Research Agenda
European Industry
Goals and Targets
Markets and Applications
Visions and Challenges
Robots and Infrastructure
Technologies
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3 Markets and Robots

The Robot Market

The robot market is evolving and diversifying. Robotics technology will impact a broad spectrum of sectors. Europe has key strengths in the global market.

Market Domains

What are the primary markets, where will robots be used? Who are the stakeholders? What are the value chains?

Robot Categories

How can robots be categorised? What are the different types?

Robot Abilities

The generic abilities of robots. What are robots capable of? How will abilities develop?

The Robot Market

The size of the robotics market is projected to grow substantially to 2020. This is a global market and Europe's traditional competitors are fully engaged in exploiting it. Europe has a 32% share of the industrial market. Growth in this market alone is estimated at 8%-9% per annum. Predictions of up to 25% annual growth are made for the service sector where Europe holds a 63% share of the non-military market.

From today's €22bn worldwide revenues, robotics industries are set to achieve annual sales of between €50bn and €62bn by 2020. However, the much larger impact of robotics arises from the effect it has upon the competitiveness of the manufacturing and service industries that use robotics systems and technologies, and upon the quality of life for citizens.

The robotics marketplace has traditionally been divided into two areas, industrial robotics and service robotics. But when looking forward to 2020 it is increasingly clear that these divisions will blur and that the robotics market needs to be viewed with a different perspective. The development of smarter and more cooperative industrial robots means that technologies are shifting from the so called service sector to the industrial, and the need to develop reliable mobile platforms transporting manipulators means that industrial robot arms are finding wider markets through diversification. It is important that this blurring of traditional distinctions is captured and exploited by the multidisciplinary nature of the European robotics community.

Europe has a technical and commercial lead in a number of key technologies and markets. The European Commission recognises the strategic importance of the European Robotics market and the need to maintain and where pos-

sible advance these leads against a rising global market. It is essential to target investment in core research and innovation to strengthen and build both the community and the market.

The global reach of the robotics market and its strategic importance mean that it has the potential to create sustained growth and opportunity within Europe. Failing to take the initiative will have a significant negative impact over the coming decades.

The diversification of the robotics market that is taking place requires a new means of analysing the market space. Key to the functioning of the SRA is its ability to link end user products, services and business models to the underlying technologies needed in the creation of entirely new markets. These linkages are paramount to the allocation of research resources and the maximising of investment impact in the market.

The diverse range of applications means that a broad range of existing industries will be revolutionised by robotics technology. In all these applications the main benefits come from improved efficiency and increased interaction and cooperation between robots and people. To deliver this technology safely and effectively will require a well focused R&D&I strategy which SPARC aims to provide.

Market Domains

Robots will eventually pervade all areas of activity, from education and healthcare to environmental monitoring and medicine. The broad spread of the future impact of robotics technology should not be underestimated.

In order to illustrate this breadth the potential markets for robotics technology have been identified and classified according to different types of market. These are divided into Market Domains where robots or robotics technology will transform well established markets; and different Robot Markets categorising producers of robots or robot technology.

The robotics market is not only composed of end user applications and robot technology suppliers but also of service and supply chains which add value. The early stage nature of the robotics market means that these are not yet fully developed.

In all of these markets the key stakeholders need to be identified and the value and supply chains analysed to ensure that the R&D&I strategy maximises its market impact.

Market Domains

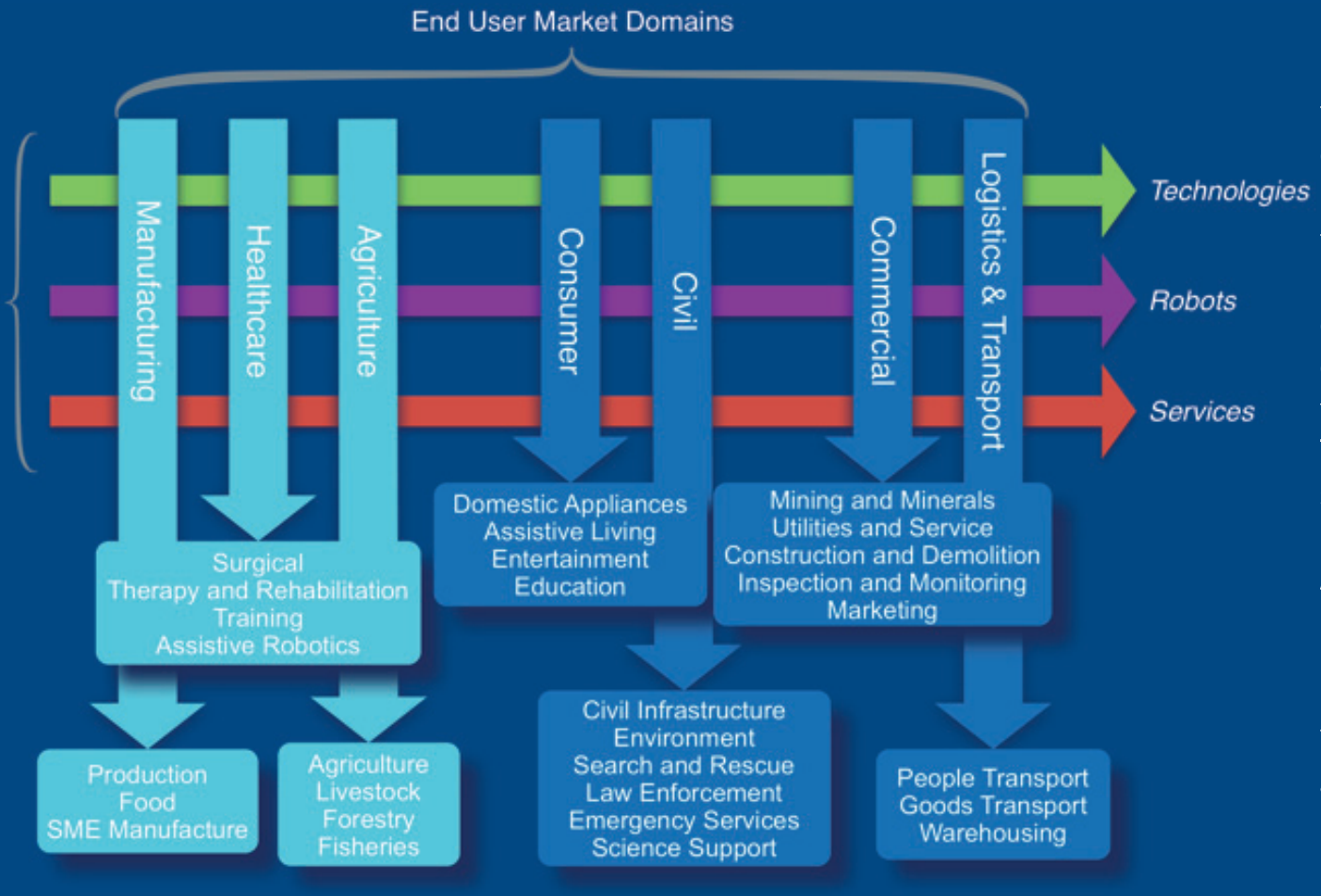
Robotics technology will be delivered into a wide range of end user market domains. As a result many of these markets will undergo significant transformation. These transformations will take place over different time scales as the deployability of robotics technology improves in each domain.

The market domains can also be categorised with regard to their specific business modes, the means of deployment, the level and type of risk and the legal and social infrastructures that are impacted.

The market domains can be clustered into the following high level categories;

- Consumer Robots,
- Civil Robots,
- Commercial Robots,
- Logistics and Transport Robots,
- Military Robots.

These high level domain categories can also be seen as encapsulating different business modes, Business to Customer (B2C), Business to Business (B2B), Business to Government (B2G) and service delivery



Under each of these high level domain categories are collections of individual sub-domains that characterise the market. These are presented in detail in the Multi-Annual Roadmap document.

From within these high level groups specific markets have been identified where where there is already strong early market development and considerable future potential. These areas are likely to create significant growth and provide strong opportunities for near market activities and technology transfer;

- Manufacturing,
- Healthcare,
- Agriculture.

Robot Markets

In addition to the market domains there are robot markets. The robot markets can be categorised according to the following categories, each of these cut across the different end user markets;

- robot systems,
- robot technologies,
- robot services.

These are product centric markets concentrating on the sale and deployment of specific types of robot, technology or service. For example the production of marine robots, or industrial robot arms, or specific aspects of robotics technology such as actuators, or sensors.

Under each of these robot market categories are a wide range of different types of producer and these are presented in more detail in the Multi-Annual Roadmap document.

Value Chains

There are many diverse value chains operating in the robotics market place. Identifying them and ensuring that they are recognised and supported will be a key task for SPARC.

In addition to the value chains based on module and component supply service sector value chains will emerge to support the growing industry, these will be characterised by providing both non-technical and technical services.

Critical to the development of all these value chains will be the role of SMEs and their ability to create technology transfer opportunities. This technology transfer, either in terms of licensing or modular delivery will be a key element in the wealth creation process across the value chain that derives from the investment in robotics.

There are key points where value is added into the chain:

- In technology transfer from research to industry.
- In technology delivery business to business through component and service supply.
- Through manufacturing robots and systems from components.
- Through financial, educational, maintenance services delivered through system deployment.
- Through system integration and adaptation in different market domains.
- Through product delivery to the market.
- Through service delivery to the market.

Key Stakeholders

The diverse nature of the robotics industry leads to a wide range of stakeholders both inside and outside of the robotics community. The developments expected in the coming decade will impact on European citizens in many areas of work and home life and will create a wide range of different stakeholders. Stakeholders can be categorised into the following groups;

- industry and service organisations,
- research organisations,
- end users, both commercial and consumer,

- government and policy makers,
- key representatives and opinion leaders within civil society,
- financial institutions.

SPARC will engage with these different stakeholder groups in order to understand their perspectives on robotics technology such that barriers to market are reduced and appropriate communications are established to enable constructive dialogue.

Manufacturing

Manufacturing has always been the mainstay of robotics application. Robots have traditionally been applied to large scale volume manufacturing in the automotive, electronics, aerospace and white goods domains. These remain strong markets and the drivers of incremental growth. Europe currently supplies over 40% of the world's industrial robots and it is important that this position is maintained.

New smarter robotic systems that can be deployed in SME manufacturing and in lower volume production are beginning to emerge. Europe has key technology in these areas that must be transferred to market to gain a competitive edge in these new emerging markets. Further impact on the manufacturing sector is also a key element in achieving the wider European Challenges concerned with increasing employment and the management of resources.

Healthcare

The use of robotics technology in healthcare already has a direct impact on the delivery of specific services, this impact will expand in the coming decade. Europe has considerable expertise in the application of robotics technology in this sector. The global market in tele-operated surgical robots has grown rapidly in the last 5 years. Opportunities in rehabilitation and hospital logistics exist that can be identified has having a direct cost saving impact. Europe's reliance on the public procurement of healthcare provides many advantages to develop and deploy systems through near market activities. Europe has numerous global healthcare equipment suppliers and there is a significant opportunity to gear up the application of robotics technology.

Robotics technology also has significant potential to impact on the European Societal Challenges concerned with the ageing society, improving health and wellbeing.

Markets

Agriculture

Agriculture is an important part of the European economy. The use of robotics technology in agriculture has been growing steadily for some time. The extensive deployment of milking robots has awakened the agricultural community to the wider opportunities offered by robotics technology. A wide range of application areas are currently under consideration from crop monitoring to livestock management and harvesting. The impact on efficiency, yield and environmental management are compelling in many areas of the agricultural sector.

Promotion of this area of application provides an opportunity to deploy large scale systems in real environments where the outcomes have the potential to impact on a wide range of related end user markets. The agricultural sector, including forestry and fisheries, also impacts across the European Societal Challenges covering food security, sustainability and the environment.

Civil Robots

This high level domain covers the use of robots within government and public agencies (B2G) for example, civil infrastructure, search and rescue, environment, law enforcement, emergency services, and science support.

These application areas are typically managed by civil authorities and the robot systems would be operated by regional and national services or by contractors engaged to do so. They will be operated by trained personnel and may be operating in hazardous or extreme environments where people may be at risk.

Applications in this high level domain range from the monitoring and maintenance of water, sewerage, and gas pipelines; electricity networks, rivers and harbours to emergency disaster recovery and civil security applications.

Markets

Commercial Robots

Robots play a vital role in the production of goods and services in commercial organisations. Other high level domains such as manufacturing and agriculture are closely related. The potential for using robotics technology in this Business to Business (B2B) domain range from mining and minerals, to applications in the service and utility sector through to construction and demolition, and retail marketing.

These Robots work as part of a commercial process so cost effective performance, reliability, and ease of use are important system attributes. These robots will also be applied to service functions within a commercial organisation. They will be operated by trained personnel, operating with or in cooperation with people in a work environment.

Potential applications range from undersea mining to the use of robots in the construction of buildings or in advertising.

Logistics and Transport

A special sector highlighted because of its key opportunities for Europe covering the following areas: transportation of goods, transportation of people, logistics and warehousing.

Autonomous and semi-autonomous robots operating within both public and private transport infrastructures, carrying people and/or goods. Robots operating in warehouses and interfacing with wide area transport infrastructures, or other internal transport systems.

Within the public infrastructure these robots will be governed by transport related legislation and approvals, which will need to be extended to cover autonomous and partially autonomous vehicles.

Markets

Consumer Robots

People will notice robots when they start to impact on every-day life. At home robot vacuum cleaners, pool cleaners and lawn mowers are readily available. The opportunity for consumer robots extends beyond these early applications covering other domestic applications, entertainment, education, monitoring and security, and assistive living. The potential for growth in this consumer sector (B2C) is regarded as very high and Europe is well placed with global companies to exploit this emerging market.

These robots will be bought or leased and used to provide services to individuals. They will be operated by, or interact with, untrained, or minimally trained people in everyday environments. Applications range from helping the elderly stay safely mobile in their own homes to the automation of everyday household chores and the provision of remote monitoring and security for the home.

Military Robots

Robots operating on behalf of the military controlled by the military infrastructure and legal systems.

It should be noted that this category exists mainly for completeness and acknowledges the large amount of development and deployment carried out in this area. However, it is not intended that programmes developed under SPARC or Horizon 2020 will specifically address this area. It is recognised that technology transfer opportunities exist from the military sector into the civilian domain.

Markets

Robot Categories

Robots can be categorised in numerous different ways but there are four key factors that distinguish them. These different characteristics also mark out potential robot markets that span the domains.

It is not possible to list all the different types of robot, or the different tasks that they can do. Many of the key applications and markets that will dominate robotics have yet to be established. It is not the purpose of this strategic research agenda nor of the roadmap to attempt to predict individual products. Instead a classification must be adopted that captures the essence of the similarities between robots. This classification scheme allows for the possibility of new forms of robot and tasks. These are certain to appear as robotics technology becomes more pervasive. Crucially the classification scheme must also provide the possibility of linking each characteristic to the implementation technologies that must be developed to realise it. Through this linkage the impact of technology development on classes of robot can be mapped and the consequential impact on domains assessed.

There are four basic characteristics of robots that distinguish them:

- Where they work.
- How they interact and collaborate with users.
- Their physical format.
- The primary function they perform.

Any particular robot can then be characterised according to these generic characteristics and the individual charac-

teristics can be linked to sets of implementation technologies. By this process it is possible to connect the design of application specific robots to the technologies that they might be composed of.

Operating Environment

There are five primary operating environments for robots;

- on the ground,
- in the air,
- underwater,
- in space,
- inside the human body.

In addition to these there are operating environments that interface between these environments. For example on the surface of water, or between the upper atmosphere and space. Many types of robot will also have to operate in two or more of these environments.

Within these primary environments are sub-divisions, deep and shallow water, indoors, outdoors and underground for example.

In addition to these physically different environments the level of hazard, to people, in each environment is also a significant factor within its characterisation. For example working at high temperatures, in an explosive atmosphere or with corrosive substances.

In each application domain different operating environments will prevail.

Marine Robots

Marine robots provide a good example of a cross domain robot market that is based on a specific type of robot.

Robots operating in a marine environment can be applied to many different market domains, Agriculture, Civil, Commercial, Consumer.

Potential applications range from allowing tourists to view coral reefs, to inspecting undersea pipelines.

Marine robots can already be found working in the off-shore oil and gas industry and in science support activities investigating the ocean currents, flora and fauna.

There is potential for their application to the monitoring of the marine environment, pollution, fish stocks etc, and in the maintenance of harbours and shipping. It is also recognised that robotic mining may be the only way of extracting the significant mineral resources that lie under the oceans.

Interaction and Collaboration

Robots are rarely if ever fully autonomous. There is always some interaction with users even if this is remote, via a communication link, for example the Mars rovers. The level of decisional autonomy a robot has is highly variable and can be represented as a continuum. Because there is a need to link capability to technology and in particular step changes in technology to step changes in the ability of robots to carry out useful tasks a set of waypoints in this continuum have been identified as significant;

- Programmed,
- Tele-operated,
- Supervised,
- Collaborative,
- Autonomous.

In addition to these waypoints on the continuum of decisional autonomy robots can also work in groups, either as collections of heterogenous robots, often likened to swarms, or as inter-operating collections of individually specialised machines each operating in its own right but contributing part of an overall process, an ecosystem of robots. Robots may also work in conjunction with other non-robotic devices and with the internet of things.

The level of autonomy and the number of robots will significantly influence the type of user interaction and therefore the technologies needed to implement the robot.

Robot Companions

It is widely accepted that one of the most significant step changes in robotics will come through their closer interaction with people. The potential areas of application are broad and range from healthcare through to helping assembly workers on a production line. It is expected that these Interactions will become more physical and more intuitive over time, gesture, touch and spoken interaction are likely to become the norm.

The potential impact of robotics will depend largely on improvements in the ability of robots to interact. In the context of robot markets it is likely that improvements in interaction will be made by organisations that specialise in this area and to realise the potential of their IP they will need to license out their technology. This will create a new market in interaction technology that is likely to be wider than just the robotics domain.

Physical Format

Robots take many different physical forms, however there are some basic types of physical manifestation that require identification;

- Robot Arms,
- Robot Platforms,
- Exo-skeletal robots,
- Metamorphic robots,
- Nano and Micro Robots,
- Humanoid.

These categories of physical form describe generic forms. The physical form does not define the technology of propulsion, so for example a robot platform may operate with wheels or legs, it may be powered by batteries or bio-energy fuel cells and it may operate in any of the different work environments.

Miniaturised Robots

The miniaturisation of robotics technology has application in healthcare and in manufacturing and represents a specialist domain of robotics technology likely to create a robot market.

In the healthcare domain miniaturised surgical tools with built in sensing will enable new opportunities in fine scale surgical procedures with particular impact in cardiovascular, neurological and oncological areas. These devices will not only increase surgical opportunity but also have the potential to reduce the invasiveness of procedures.

The use of robot manipulation in the industrial production of complex miniature devices is also an emerging area of application, with particular application in micro-optical systems and the volume assembly of micro scale components. The electronics industry has pioneered special purpose miniature assembly robots. It is expected that generic miniature robot tools will impact on manufacturing in the coming decade.

Function

Robots can carry out a wide variety of different functions. Most robots combine a number of basic functions to perform a task. It is not possible to detail all of the different functions a robot can perform. The product visions presented in this document and in more detail in the Multi-Annual Roadmap document give an indication of the range and type of tasks that robots might be able to achieve. It is however possible to give a high level view of some of these basic functions, they can be characterised as follows:

Assembly: Joining parts together, this may also involve a fixing process such as welding.

Surface Process: The function of applying a process to a flat surface or the surface of an object. This could be spraying a coating, abrading, cleaning, scraping, drilling holes or cutting it.

Interaction: The function of interacting with ether a human or another machine or robot. Interaction involves either direct physical contact between the human and the robot or the exchange of a physical object or information between the interacting agents.

Exploration: The function of exploring an unknown or partially known space with the goal of mapping that space or the specific goal of, for example, finding a person, resource or location.

Transporting: Transporting involves orienting and moving objects or people between known start and end locations, movements may be over short or long distances.

Inspection: A function that covers a space, known at some scale, and scans that space for specific parameters, for example monitoring water pollution in a harbour.

Grasping: The function of holding and orienting an object, tool or person. Includes firstly identifying and then working out how to hold the object. For example picking up a glass of wine.

Manipulation: The function of utilising the characteristics of a grasped object to achieve a task. For example using a pair of scissors, or unscrewing a light bulb with a two-finger gripper.

Most robots combine these basic functions to execute more complex tasks. As new robots are developed this list of functions will grow.

Robot Abilities

Robot systems are complex integrations of a wide range of different technologies. There are abilities that all of the different robot types share and which characterise whole system operation. Each robot will need a selection of these abilities. Abilities allow benchmarks for performance to be set.

In order to describe these abilities a baseline of characteristics is needed. The different abilities need to be defined independently of any particular robot configuration or domain. Abilities provide the basis for performance metrics.

Each ability captures one specific aspect of the operation and behaviour of a robot system. For each different type of robot there will be key abilities that can be identified and defined in detail. This list of abilities aims to cover all the different types of ability that robots possess.

The Multi-Annual Roadmap document provides extended detail and describes ability targets.

Configurability

The ability of the robot to be configured to perform a task or reconfigured to perform different tasks. This may range from the ability to re-program the system to being able to alter the physical structure of the system. (e.g. by changing a tool).

Adaptability

The ability of the system to adapt itself to different work scenarios, different environments and conditions. Adaptation may take place over long or short time scales. It may relate to local control systems or actions, to the whole system or to interaction.

Interaction Ability

The ability of the system to interact both cognitively and physically either with users, operators or other systems around it, including other robots. The ability to interact may be as simple as the use of a communication protocol, or as advanced as holding an interactive conversation with a person.

Dependability

The ability of the system to perform its given tasks without systematic errors. Dependability specifies the level of trust that can be placed on the system to perform. This may be in terms of a MTBF or that we trust it to look after a person for a day.

Motion Ability

The ability of the system to move. Motion may be highly constrained where ability is measured by the precision of the motion, or its repeatability. Alternatively motion may be unconstrained and is measured by the ability to move effectively in different media or between media. For example in unstable environments such as on ice or sand where the target is to maintain balance or achieve effective motion.

Manipulation Ability

The ability of the system to handle objects. Where end effectors are fixed or specific to the task this will specify the accuracy and repeatability of the manipulation, for example the ability to absorb tolerances between parts during assembly. For dexterous manipulation it might specify the ability to discover how to hold and move unknown objects, or the ability to match two objects together in specific ways.

Perception Ability

The ability of the robot to perceive its environment. At the simplest level this is about specifying the probability of accurately detecting objects, spaces, locations or items of interest in the vicinity of the system. It includes the ability to detect the ego motion of a robot arm and the ability to interpret information and to make informed and accurate deductions about the environment based on sensory data.

Decisional Autonomy

The ability of the robot to act autonomously. Nearly all systems have a degree of autonomy. It ranges from the simple motion of an assembly stopped by a sensor reading, to the ability to be self sufficient in a complex environment.

Cognitive Ability

The ability to interpret the task and environment such that tasks can be effectively and efficiently executed even where there exists environmental and/or task uncertainty. The ability to interpret human commands delivered in natural language or gestures. The ability to interpret the function and interrelationships between different objects in the environment and understand how to use or manipulate them. The ability to plan and execute tasks in response to high level commands. The ability to work interactively with people as if like a person.

Applications

4

Application Scenarios
A glimpse of possible applications from across the different market domains.

Societal Challenges
Long term societal challenges where robots can have a significant impact.

Application Scenarios

Application scenarios provide a window onto the range of applications and markets that robot technology might be applied to by 2020. These scenarios are a small sample of what will be possible.

Robotics technology will have a wide impact on a diverse set of markets. While robotics will create new markets and opportunities it will also have a significant impact on a broad spread of existing markets from healthcare to agriculture. The creation of a viable robotics industry in Europe will depend as much on these traditional sectors embracing robotics technology as it will on the creation of new robot markets. This inclusive duality is an important part of the robotics strategy in Europe.

The robotics market will be composed of robot component integrators and manufacturers, installation and service companies as well as design and development practices. These support companies will be a key element in the push of robotics technology into traditional market sectors within Europe.

The domains that will be most impacted by robotics technology can be clustered into broad market segments with common interests and infrastructure.

- Manufacturing
- Healthcare
- Agriculture
- Civil
- Commercial

- Logistics and Transport
- Consumer

Each of these broad market domains will involve a range of specialist robotics companies alongside established companies together with supporting services and infrastructure management. The impact of robotics will vary from domain to domain. Robotics can offer new ways of delivering services, and ways of delivering new services. In existing markets robotics technology can extend the line of products providing additional functional benefit, or create new types of product.

Robotics has the potential to transform many areas of business from manufacturing to healthcare. No more so than in areas where robots and people closely interact and collaborate. Robots are already serving as life-saving surgical tools, smart rehabilitation trainers, as well as reliable movers in all kinds of logistics scenarios; their role, impact and interaction with people will only grow.

The following product visions provide a brief glimpse of what might be achieved by 2020. These visions are drawn from examples prepared by experts working in each domain and so represent a snapshot of the expectation in that domain. The Multi-Annual Roadmap document provides more in depth detail of each example and links the visions to the underlying technology capabilities that will be needed to achieve them.

Manufacturing

Technology

- Accurate indoor positioning systems for mobile manipulators, particularly in dynamic environments.
- Sensor based safety systems to enhance human robot interaction.
- Higher levels of realism in system modelling to speed application development.
- Reactive planning and control able to operate a robot safely in real industrial environments.

Description

Europe needs to maintain and grow its manufacturing base to increase employment and stimulate the wealth creation cycle.

The higher cost of labour means that automation is a key element in the growth of manufacturing. In particular manufacturing in SMEs can be automated to drive down cost. This type of mid to low volume high value added manufacturing requires low installation and running costs and a high degree of flexibility, which cannot typically be provided by traditional large scale manufacturing robotics. Re-shoring is also likely to be driven by the availability of highly flexible and easy to use manufacturing robots. The merging of smart technologies, trainable systems, and intuitive user interfaces with compliant robot manipulators creates an opportunity to make a range of smart manufacturing robots that will enable automation in small and mid scale companies, manufacturing a wide variety of products, to extend their markets by reducing costs, resulting in expansion and a consequential increase in employment.

Time Scale

Robots have been used in manufacturing for some 50 years and continued incremental growth is strongly expected. The new market for smarter manufacturing robots which can be intuitively reprogrammed is starting to grow as awareness and availability of this technology increases. If the extended use of robots in manufacturing is to have an impact on employment then this needs to make significant progress in the next five years. The use of robotics in food preparation is also expected to expand in the coming decade.

Scenario

Peter's family had outsourced 75% of its basic component manufacturing to the far east ten years ago, seven years ago half of its sub-assembly manufacturing was outsourced. Pricing was good but design changes often take a long time to work through the China office and out to the factories. Costs are also rising, transport costs in particular, and fluctuating exchange rates force greater contingency margins. Customers have started to expect a more bespoke product, individuality, changes to design and style each year. The need to accurately predict sales in a changing and competitive market in order to get the best price has made business tougher.

Investment in automation was a tough decision, the changes needed in the factory and the restructuring of the business back towards manufacturing required the regaining of skills once common in the factory. Peter clearly saw that the alternative to automation was steady decline either from new companies with higher investment levels reacting faster to new markets, from overseas competition taking over traditional markets.

Two years on and manufacturing is back in Europe. The ability to turn round new designs and produce limited batches, the ability to make to order and still be competitive on price, the ability to immediately respond to advertising has altered sales techniques and opened new markets. Export orders are up and three new sales staff have been taken on. The new robot machines can be trained by hand and work easily along side the remaining elements of manual production. The design department understands the limitations of the shift to automation but is now discovering new opportunities only possible with highly flexible automation.

Impact and Market

The use of robotics in production is a key factor in making manufacturing within Europe economically viable. In order to improve competitiveness manufacturing unit costs need to be reduced and robotics provides a means to achieve this. Locating manufacturing in Europe reduces delivery times and costs and robot assembly techniques allow a much greater degree of customisation and product variability. The market for manufacturing robots is strongly expected to grow through diversification into industries with lower volumes, and into areas of manufacturing where manual assembly has previously moved away from Europe.

Healthcare

Description

Healthcare is a significant and growing sector for the application of robotic technologies. The main application areas that are currently identified for significant growth are; the application of robots in assisting surgery and diagnosis, the use of robots as training tools for the medical profession and the therapeutic use of robots in applications such as rehabilitation. In the medium term it is also expected that robotics will impact on assistive technology particularly for the elderly both in care and at home.

The opportunity to apply robotics technology exists not only in patient care but also in the logistics of running large hospitals. This may be an area where cost savings can be achieved. The use of near market instruments under Horizon 2020 is expected to have a significant impact in identifying primary opportunities.

Technology

- Improved teleoperation and physical interaction
- Miniaturised mechanical systems and sensing
- Multiple degree of freedom tactile feedback
- Inherently safe systems
- Monitoring of patient condition and improved data interpretation during procedures

Time Scale

Tele-operated surgical systems have been increasingly used over the past ten years. While the case for their use is complex it is strongly expected that there will be an increasing number of different procedures carried out using tele-robotic technology in the coming decade. The use of robots for training and in therapy is in its early stages of development. The use of robots for rehabilitation is expected to expand significantly in the coming decade.

Scenario

John, aged 14, was beginning to forget the pain of two weeks ago. His knee twisted in an ill-advised football tackle. Minor surgery to reconnect the ligaments, performed by a semi-autonomous robot surgeon, he could just about watch the complementary video without wincing. Now he was sitting in the machine the hospital had sent him home with. Its mechanical structures printed to match his leg and foot size. Its sensors monitoring his exertion and extension a comforting voice telling him to slow down. The repetitive exercises were starting to get boring; he felt he should be back playing again.

Rehabilitation session finished, the machine reprogrammed the now recharged wearable knee support, altering the stiffness and dynamic response to account for his improved swing. The rehab machine unlocked the brace around his leg with a smooth whir and he felt the full weight of his lower leg again with a slight twinge. Maybe the machine was right, no football yet.

His mother reattached the wearable knee support so that he could get to school on time, thankful that they weren't having to make a hospital trip every week.

Impact and Market

The impact on surgical outcomes is becoming well understood and this will help guide the future applications of tele-operated surgical machines. Europe has considerable expertise in the application of robotics in healthcare and it is important that this is geared up so that innovations reach the market place.

It is also expected that robotics technology will have an impact on the training of clinical professionals through the use of physically interactive systems able to provide direct experience without risk and to simulate specific conditions in order to better prepare clinicians.

In rehabilitation robots can provide the repetitive and progressive exercise based on measured patient progress that is known to provide better outcomes. In time such systems may become portable and deployable in patients homes.

Agriculture

Technology

- Predictive and distributed planning
- Crop and livestock assessment and recognition of condition
- Produce handling and processing
- Synchronisation and coordination between farm vehicles and with processing equipment.
- In-field localisation and communication.

Description

There are a considerable number of applications for robotics technology in Agriculture. A small number have already been successfully automated. The advantages are significant in terms of improved yield, land use, environmental impact and management. The ability to gather data and assess the state of crops and livestock provides significant opportunity for efficiency improvements. Extending robotics technology to fruit and vegetable harvesting will provide further opportunities to provide in-field processing and packing.

The use of autonomous or semi-autonomous farm vehicles that can communicate and synchronise movements will enable the seamless transport of crops from the field to ensure an even and efficient flow of product into the packing and distribution system. Selective harvesting produce in optimum condition leaving unripe product in the field to mature will improve yields. Traceability will be built into the system, each load tagged at source with field and crop data, farm statistics, yields monitored, soil condition, pest levels, and nutrients all monitored as harvesting proceeds allowing “big data” processing to optimise the farming process.

Time Scale

Milking systems are already widely deployed. First stage semi-autonomous farm vehicles are close to market in a number of applications. Within five to ten years the levels of automation are expected to increase significantly particularly in arable farming and livestock management.

Scenario

Jacob 55 grew up on a farm, he drove his first tractor at the age of 12. Today the wheat harvest starts. The two combine harvesters are lined up waiting for the field data network to boot. A few minutes later the start button turns from orange to green and he hears the ready sound in his ear phones. He pushes the button and the two combines move off in unison. The mutual exchange of location data and the sharing of sensors across the network allow the two complex machines to work together efficiently.

The grain lorry waits at the edge of the field. Once registered onto the local data network it starts communication with the combines. Its driver presses the start button and the lorry, now under the control of the combines, approaches them. Grain starts to flow from the silos within the combine. Sensors monitor the flow of the grain and know the capacity of the lorry. Its path back to the road plotted to minimise ground compaction. It stops at the field edge and logs out of the network, manual control handed back to its driver.

Jacob checks over the systems and dispatches the remote combine to the field edge as he finishes the final strip. In convoy they move to the next field.

Impact and Market

Agriculture is cost driven, unit costs and yield improvements are the only real argument for automation. However automation is also expected to deliver on improvements in environmental impact for example with selective pesticide dosing, reduced levels of ground compaction and higher levels of land utilisation. Within the supply chain from field to shelf the ability to synchronise the delivery process should enable smoother flows to processing plants and faster delivery times. The use of greater in-field processing will reduce the need for post-processing and the improved crop yields make the farming process more cost effective.

Improved planning systems and better data capture will enable a “big data” approach to farming impacting on the overall efficiency of the wider system.

Civil

Description

The delivery of services by civil authorities provides an opportunity to deploy robotic technology to increase service levels and provide additional services more cost effectively. Across Europe a broad range of services are managed by civil authorities. Typical potential applications include civil infrastructure services, such as urban maintenance and cleaning; policing services, such as border and site surveillance, or crowd management; emergency services, such as disaster management or Search and Rescue; rural services, such as environment surveillance, Law enforcement services such as human officers support in routine prevention operations. There is continuous pressure to reduce costs and yet increase or maintain these services.

Some aspects of civil application involve the use of multiple robot systems utilising data gathered form different locations and operating environments integrated with human operators and semi-autonomous systems.

Technology

- Mission and task planning, particularly between multiple modalities.
- Sensing, perception and interpretation of the environment.
- Cooperative and distributed planning for multiple robots.
- Cognitive technologies for assessment and high level interpretation.
- Human robot interaction.

Time Scale

Some applications are already being targeted, not only with teleoperation. In 5 to 10 years autonomous inspection in the air and under water will become more effective.

Scenario

Karl works as the deputy manager of inspection autonomy at a large container port handling cargo ships from all over the world, 24 hours a day seven days a week. Built up over 30 years it contains buildings and infrastructure predating the digital era and in varying condition. New regulation on pollution, import restrictions, safety, and the need for continuous operation require continual inspection and monitoring.

He and his team of five, manage the integrated fleet of autonomous air and sea vehicles, some 200 in total, that inspect and monitor the the 50 square kilometres of the port. It is raining and there is a mist hanging over the port.

A pollution monitor vessel has detected an oil spill in one of the busier docks and is now monitoring the extent of the spill and its underwater volume. Karl approves its request for assistance and three other monitor craft are directed to help. Ten air vehicles self-preparing with the correct dispersant for the oil type. Karl careful examines the data as it arrives from the monitors when they surface to communicate.

Slowly a picture of the spill emerges together with the prediction of its drift with currents and tides. A sample analysis identifies the source of the leak and the ship operator is contacted. He approves the dispatch of the boom control vehicles as they will take the longest to arrive. The port wide data system provides them with navigation through the busy harbour moment to moment.

The spill volume assessed he dispatches 5 dispersant drones. He sits back and monitors the other 5 on-going monitoring actions happening at the same time, regular inspections of infrastructure, underwater maintenance of shipping channels, pollution monitoring at the oil terminal. All without interrupting the operation of the port.

Impact and Market

Many different markets will use robots for environmental monitoring: area surveillance of people and goods, monitoring crops from the air, emissions from industrial processes, water quality in harbours and at sea. Inspection of the civil infrastructure, bridges, reservoirs, power lines can all be carried out more efficiently with robot help including the ability to work 24/7. The ability to maintain the nuclear power infrastructure may depend on robots being able to carry out maintenance tasks that would otherwise be impossible, thus significantly extending the lifetime of reactors. Similar impacts on other major civil infrastructures such as roads and pipelines also have the potential to reduce costs by identifying maintenance issues earlier.

Commercial

Technology

- Safety integrated design processes
- Physical human robot interaction
- Long term autonomy
- Light weight robust mechanical structures

Description

Robotics technology has been used in the oil and gas sector for many years. It is now finding use in mines and in tunnel construction to reduce risks. Utility companies manage wide spread infrastructure that needs to maintain high availability and robotics technology will contribute to inspection and maintenance tasks. There is potential application in low cost construction and building maintenance. Commercial cleaning in public spaces, and in the transport network all lend themselves to robotics technology although in most cases the economics are difficult to justify. In the retail sector the use of robots to market products and provide a physical interface to services is beginning to be explored.

Time Scale

Continued incremental use of robotics is expected in the mining, minerals and utilities and service sectors. Applications will be driven by cost effective delivery of services and niche applications are likely to emerge in the coming five to ten years. The early diagnosis of potential problems in the energy supply chain provides an opportunity for utility companies to deploy robotic monitoring, this is expected to develop significantly in the coming decade. Commercial inspection tasks are likely to expand their use of aerial and marine robotics in the coming decade. It is expected that the retail use of robotics will increase as the cost of deployment reduces.

Scenario

This was the first time Kurt had worked on an automated building site. He wasn't sure quite what to expect. He was a fully qualified xskeleton operator and was bored of working in the shipyard, build houses sounded interesting. The site foreman showed him round. Bright yellow machines seemed to be on or in every house being built, thick black cables stretching back to power units. Trench diggers, concrete extruders, window fitters, roofers each machine playing its part. Each group of houses under construction with an xskeleton operator. Tasked with moving the building machines between tasks and sorting out problems, jammed feeds, unexpected tree roots, and making sure the automated supply trucks unloaded correctly. Kurt buddied up with John who will take him through the daily build cycle. Kurt's simulator training the day before meant he knew how it was supposed to work, but there was always something different in this type of job.

Kurt sat back eating his sandwich, looking out over the site, machines continued to move and work, xskeleton operators shifting loads, in an hour the sun would be up.

Impact and Market

The impact of robotics technology in the mining and mineral sector is already well understood, both in terms of risk reduction for workers and in terms of maintaining a working infrastructure.

There are similar opportunities for application in other parts of the utilities sector in the maintenance of power lines, and in other widely distributed service infrastructures.

In commercial cleaning the economic comparison with low paid workers is a barrier to deployment and development. In the construction sector as deployment costs lower there may be an impact on some functions particularly in the use of co-workers and exoskeletons.

The novelty aspect of retail use will accelerate once deployment costs reduce. Longer term retail use will depend on the impact and effectiveness of the deployed technology.

Logistics and Transport

Description

Warehouses are well organised and increasingly robots are deployed on a large scale to pick and organise items for delivery. While there are still efficiency gains to be made from optimising the automation of large warehouses the entry and exit of goods from the warehouse is still a potential bottleneck. Automating the unpacking of containers and pallets and the automatic stacking of lorries are the next steps in reducing costs in the delivery process. These tasks will involve significant interaction with people as they collaborate to pack and unpack goods.

Technology

- Interaction technology.
- Compliant mechanical systems.
- 3D environment interpretation.
- Task planning and optimisation.

Time Scale

Incremental milestones in niche areas of warehouse management may be realised within a few years. It will take 10 to 15 years for highly reliable, cooperative systems to be deployed.

Scenario

Andrew settles into the autocar, states his destination and the door closes. He accesses his documents and starts work. The autocar joins the flow of vehicles heading out to the industrial zone. His parking space is booked and the transit to his office planned into the zone personal transport system. The autocar trims its speed to synchronise arrival at the port.

He looks up at the grey sky, some things are still unaffected by robots. Andrew manages 2000m2 of autonomous systems in a general purpose manufacturing plant specialising in wooden products. Today they are making 5000 wooden garden seats, tomorrow 10000 “crafted” fruit bowls. Raw materials arrived overnight while the final batch of yesterday’s product was completing. Two hours to clean down machines and changeover tools and manufacture starts again at 8:00.

The factory employs three technical staff to deal with maintenance and system programming and a wood specialist able to design products to order and devise the manufacturing sequence and a small sales team. Each work cell can produce a single item or work in sequence with the next. Material is fed from the stores to the factory floor by a collection of mobile platforms working together to transport individual items or pallets of parts and materials. Finished goods are sent to the packing bay at the rear of the factory, packed and made ready for automatic transport to the local hub warehouse.

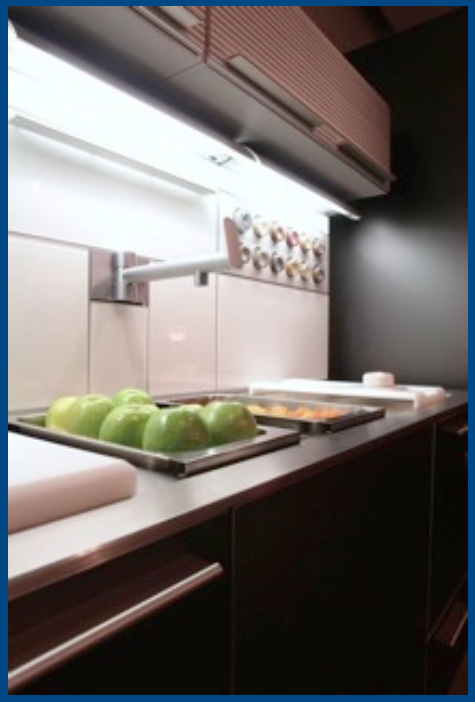
The whole system is self monitoring, inspection and quality control fully automated.

At 8:00 Andrew clicks the start button having checked the night schedule and maintenance reports. A red beacon flashes, the factory starts. Andrew’s autocar glides to a halt.

Impact and Market

The major impact will be in the reduction of costs in the warehouse and in delivery systems, this will affect manufacturing industry, parts distribution, food and goods distribution. The potential when combined with autonomous transport is to address the challenge of “warehouse to door” systems providing a near optimal delivery process.

Consumer



Technology

- Improved sensing of the surrounding environment.
- Improved interpretation of the environment.
- Low cost sensing
- Physical human robot interfaces.
- Improved energy efficient systems.

Description

The market for domestic robotic appliances; floor cleaning, lawn mowing and pool cleaning is well established. There are numerous suppliers in the floor cleaning sector, however the level of market penetration is still very low. Step changes in function may be required before autonomous cleaners become a first choice device. Other application areas for domestic appliances are at lower levels of maturity, for example window cleaning and security robots. The consumer domain also covers education and entertainment where there has been niche development over the past decade with toys and kits.

The societal impact of applying robotics technology to assistive living in the consumer market has considerable potential. These present significant challenges to all technology areas, not least in human robot interaction and in making compact efficient machines. Early applications are likely to centre on mobility assistance within the home and later extend to other life functions. The ageing society provides a strong imperative to develop these systems.

Time Scale

It is strongly expected that the domestic appliance market will achieve significant growth in the coming decade as it becomes more cost effective to deliver more complex and smarter technology. Cost and dependability are major driving factors. Other domestic applications will also come to market as the technology becomes available. The same technology will also drive applications in entertainment and education where incremental progress is expected.

It is expected that the introduction of assistive aids using robotics technology will take some time to establish, early examples of robot arms and semi-autonomous wheelchairs already exist in the disability market. The wider application of robotics technology in assistive aids for the wider population is still under development and it may take a decade before devices are deployed.

Scenario

Jo shuts the front door behind her, the children are scrambling into the car, they drive off to school. Behind her the breakfast table is a mess. The kitchen floor has crumbs and bits of cereal on it. There are clothes on the bedroom floor, books and a magazine in the lounge. The bathroom floor is wet and a towel is draped over the side of the bath. A tap is running in the downstairs wash basin. The lights are on in the hallway.

Jo opens the door the children rush in, school bags flung to the floor. The smell of supper cooking wafts through the house, she remembers what she ordered via the phone app at lunch time, after being prompted. The kitchen is clean and tidy, along with every other room in the house. A load of washing is finishing its spin cycle. The dishwasher is half full waiting... The lights are on again in the hallway.

The front door bell rings. The supermarket delivery has arrived. Jo packs the items away each one scanned into place. The children play before supper. Jo calls them as she sets the table. A green light on a closed kitchen unit fades on and off slowly then stays lit; the system is ready to start again.

Impact and Market

The primary impact of robotic domestic appliances is in saving time by offloading everyday chores. For this to be effective these robotic appliances must be functionally dependable. Once this is established the market will accelerate. A secondary effect is that these functions will be carried out more regularly and ubiquitously.

In education the use of robotics to engage children in science and technology is already well established, it is possible this may extend to other areas of study and ultimately into sports coaching. As the cost of robotics technology reduces the opportunities to develop toys based on robots will expand just as it has with embedded computer technology.

The long term societal impact of assistive technology for mobility is considerable. The ability to monitor and assist the elderly at home has the potential to make a significant impact on the challenges presented by an ageing society.

Societal Challenges

In certain areas of application robotics has a pivotal role to play in addressing some of the key societal challenges facing Europe and the rest of the world in areas as diverse as demographic change, health and well-being, food production, transport and security.

Robotics will be fundamental to meeting these challenges sustainably, humanely and cost-effectively. In each of these challenges there are future opportunities that stretch technical capability, organisational structures and the ingenuity of the community.

The following major European societal challenges have ben identified and are specifically target within Horizon 2020. Robotics technology has the potential to impact on a number of these challenges both directly and indirectly.

- Health, demographic change and wellbeing;
- Food security, sustainable agriculture, marine and maritime research, and the bio-economy;
- Secure, clean and efficient energy;
- Smart, green and integrated transport;
- Inclusive, innovative and secure societies;
- Climate action, resource efficiency and raw materials.

By their nature these challenges are beyond the reach of current technical capability, they require the cohesive integration of a wide range of different expertise and corresponding changes in infrastructure and societal and legal

frameworks for their eventual implementation to be effective.

The potential of robotics technology to provide improved healthcare in a clinical setting is well understood. The long term impact of robotics on the challenge of demographic change through the provision of assistive robots and companions to help an ageing population requires step changes in technical capability.

In agriculture and food production robotics offers clear advantages both to raising efficiency and yield, avoiding waste and providing increased food security by maximising the utilisation of resources. The long term impact of robotics technology in this area is likely to be significant.

Remotely operated robots have played a significant role in the provision of oil and gas from under-sea sources. The potential of robotics in maintaining and decommissioning key energy infrastructure in order to provide security and minimise environmental impact is widely recognised. Nuclear plant, pipelines and distribution networks can all benefit from advances in robotics technology.

Robotics technology has the potential to deliver an important part of achieving smart integrated transport, improving road utilisation, reducing accidents and fuel consumption and improving congestion by optimising flows. Coupled to transport communication networks the sensor information gathered by autonomous vehicles will provide the raw resource for traffic monitoring and management.

Finally, automated manufacture can play a role in minimising waste and in optimising the use of resources. Robotics has the potential to cause manufacturing to be relocated back to Europe with a consequential impact on long distance transport and the better utilisation of raw materials sourced within Europe.

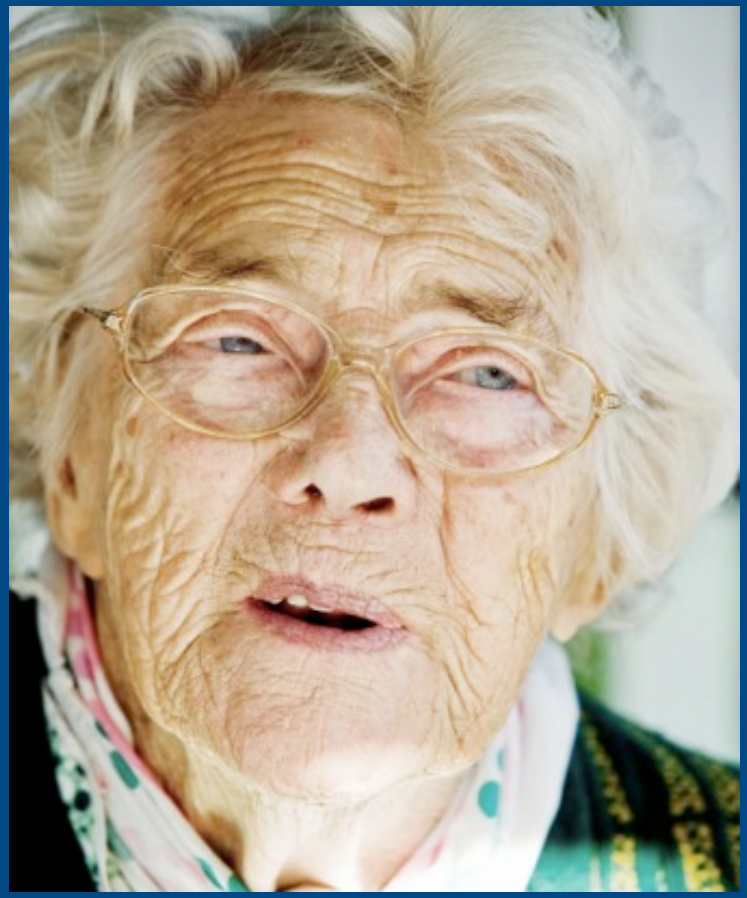
In each challenge there are clear intermediate milestones and goals, valuable in their own right, that can be achieved, but which on their own will not necessarily lead to the integrated solutions these challenges require. Only a structured and integrated collaboration between academia, industry and the public sector can hope to achieve these goals and SPARC provides the mechanisms for the genesis of this collaboration.

Achieving these long term goals requires foresight and persistence driven by the knowledge that their impact will be transformative.

If Europe is to meet these challenges then it must resource their solution. They affect Europe just as directly as they affect every other major competitor. It is not in Europe's interest to stand by and wait for others to produce solutions. Instead Europe should be aiming to create global markets from them.

The following brief outlines represent a taste of what might become possible in the long term.

Ageing Society



The demographic shift to a European population with a far higher proportion of elderly people is well understood. The percentage of elderly people in many European societies will exceed 30% by 2050.

Caring for this older population will place a significant burden on a generation of younger people and on the state. Finding effective technical solutions to providing care for elderly people is one of a range of measures required to reduce the social and economic impact of this future change.

Robotics has a part to play at many stages in this challenge. Firstly in providing automation in the home through improved autonomous systems for everyday activities such as cleaning and food preparation, allowing an older person to maintain their living environment with less external help. Secondly in providing personal assistance in mobility and personal care as these tasks restrict the ability of the frail elderly to continue living at home. Robots may also be able to provide cognitive support as well as being able to monitor a person's state either summoning external help when needed, or simply providing social contact. These robotic systems will need to integrate into communication frameworks and remote health monitoring systems, into the internet of things and home appliances that will have grown in their ability to be controlled remotely.

Through physical interaction Robots can provide assistance when needed, aid mobility, and reduce barriers to independence. This physical assistance will enable longer life, and, when used to promote exercise and wellbeing, provide a preventative benefit to counterbalance the ageing process.

Secure Energy

The growth of the civil infrastructure has been rapid in the last 50 years both on land and at sea, driven by growth and prosperity.

While much of this infrastructure can be easily replaced and transformed there are parts of it that are hazardous and represent an environmental challenge during decommissioning and replacement. As this hazardous infrastructure decays in the coming decades it will become more critical to increase the rate of decommissioning. In many cases these installations contain unknown challenges. It is widely understood that robots can play a key role in first providing accurate assessments of the state of these structures without endangering people and to maintain a periodic assessment so that rates of deterioration can be monitored and timely action taken. Secondly robots can be designed to carry out this decommissioning which often has to take place in environments hazardous to humans.

Robots can cooperate in ways that humans cannot, they can endure for longer under hazardous conditions and use sensors to monitor and inspect progress far more efficiently than a human can. The effect of this deployment will be to reduce risk and costs and ensure progress is not limited by human skill shortage, nor by uncertainty.

Smart Transport

There is considerable worldwide interest in autonomous transport. Robotics technologies are at the core of this challenge.

The increasing automation in warehousing combined with autonomous transport provides the opportunity to automate from “warehouse to door”. This implementation of wide area automation will be applicable to retail chains such as supermarkets where loading and unloading systems can be installed at each end of the delivery process. The incentive to automate this type of goods transport is based on greater levels of stock control and faster restocking times.

These types of systems may still be viable even if the range of transport autonomy is incomplete (for example restricted to motorways) because a significant part of the gain is in the packing and unpacking of goods vehicles and the integration into local warehouses. In time smarter road transport has the potential to provide a truly flexible integrated transport system with on demand, small scale, transport handling the “final kilometre”.

The impact of autonomous transport on both road utilisation and energy consumption will take time to take effect. The transport infrastructure is well established and it will require adaptation to accommodate the often envisaged close convoy car trains. The more immediate application of robotics technology in warehouses and in delivery systems will provide more immediate benefits.

5 Technologies

Robot Technologies
An introduction to technologies and how they are identified. The impact of technology step changes.

Technology Clusters
Technologies can be grouped into clusters based on the impact they have on robot design goals. Details for each key technology and targets for 2020.

Technology Combinations
Combining technologies across technology boundaries creates new opportunities.

Technology Assessment
Examining the capability of individual technologies and the need for a benchmark process for technologies that allows progress to be measured.

Robot Technologies

Robots are the result of integrating a wide range of technologies. Many of these technologies are exclusive to robotics. 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 gaining keystone IP and first to market advantage.

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. Access to the full spectrum of technologies is needed to build a strong robot market.

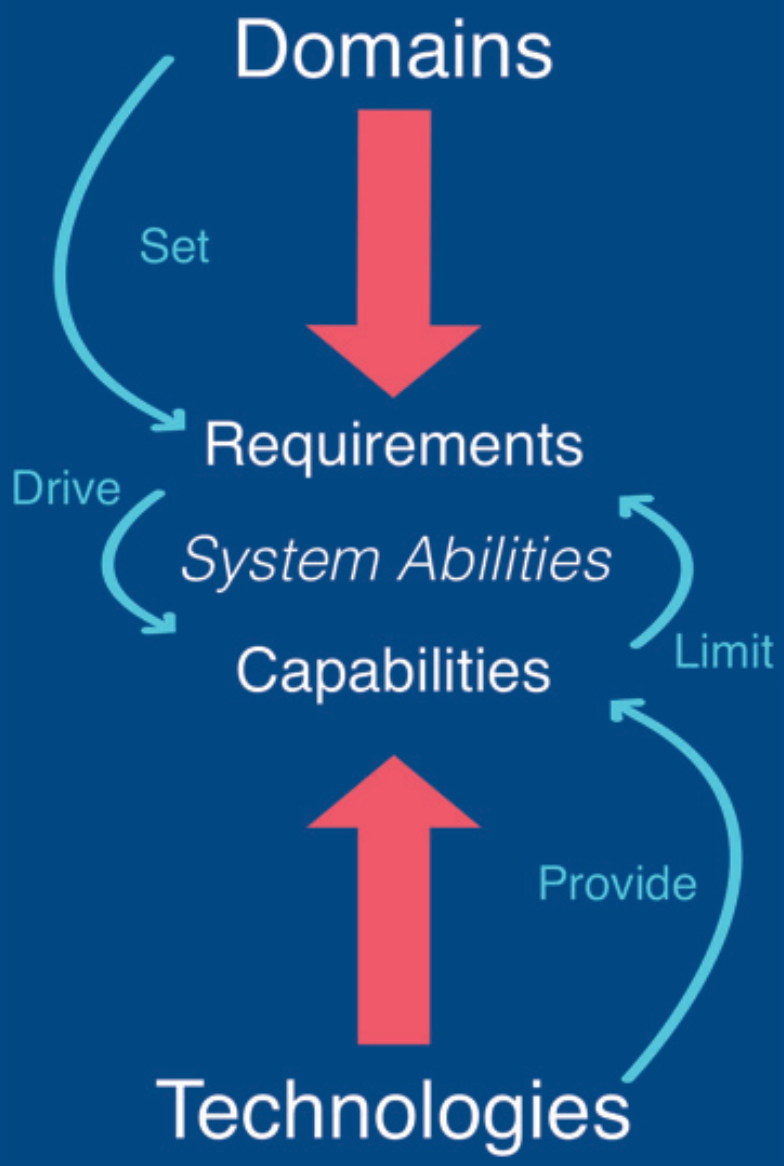
While a number of technologies used within robotics are imported from other domains (for example battery power supplies and communication systems) the primary technologies that build robots are developed within the robotics community. In seeking to build a strong technical base within Europe both investment in fundamental research, and the means to bring technology to market are equally important.

For those technologies that are not directly developed within the robotics community it is still important to understand their place in the spectrum of technologies and to understand the limitations that will be placed on products by their capability progression.

Technologies cross boundaries between application domains. Each application domain can therefore benefit from an underlying investment in technology. In order to maximise the effect of that investment priorities must be

set against each technology. These priorities need to relate to perceived future market and industry need, and to patterns in global expertise. Maximising the impact of funding on a market domain will depend on identifying the key technologies that will enable that domain. The Multi-Annual Roadmap provides different means of mapping between application domains and technologies, and highlights the development priorities in each domain.

It is important for successful innovation that advances in a particular technology are propagated to all domains, so that diverse applications can benefit from the advance. The impact of any particular advance may differ between domains, but



incremental improvements in products are driven by capability increments in technology, and increments in technology are driven by research investment.

As the robotics market grows it will be able to influence a wider range of technologies. As robots become ubiquitous the special requirements they place on technologies not currently driven by robotics e.g. communications protocols, battery technology, materials and sensors will begin to drive and influence developments in those technologies.

The technologies used in robots can be categorised into a number of technology clusters. Each of these clusters of technology can be developed independently

Technology Clusters

Every technology cluster will impact on the market. What is important is not perfect definition but the expression of direction.

The underlying technologies are characterised by encompassing a common set of methods and techniques that can be compared. The higher level clusters represent collections of technologies that have a common impact on robotics.

The fine interlinkages between the underlying technologies mean that these overview clusters do not have well defined boundaries, aspects of some technologies will straddle the boundaries and contribute to more than one of the developmental goals.

It is useful to present a high level overview of the various robotics technologies to highlight the key objectives for technology development. Characterising the relationships between technologies and between clusters illustrates the interconnections.

Technology combinations, detailed later in this document, straddle the space between the clusters and highlight areas of critical importance.

To Improve Design Methods And Systems. Better Systems And Tools

Robot development and deployment processes and the operational systems inside the robot are intricately interlinked. Robots are complex integrated systems and design processes have a key role in achieving effective, functioning, deployable systems.

To Make Better Robot Machines. Better Robots

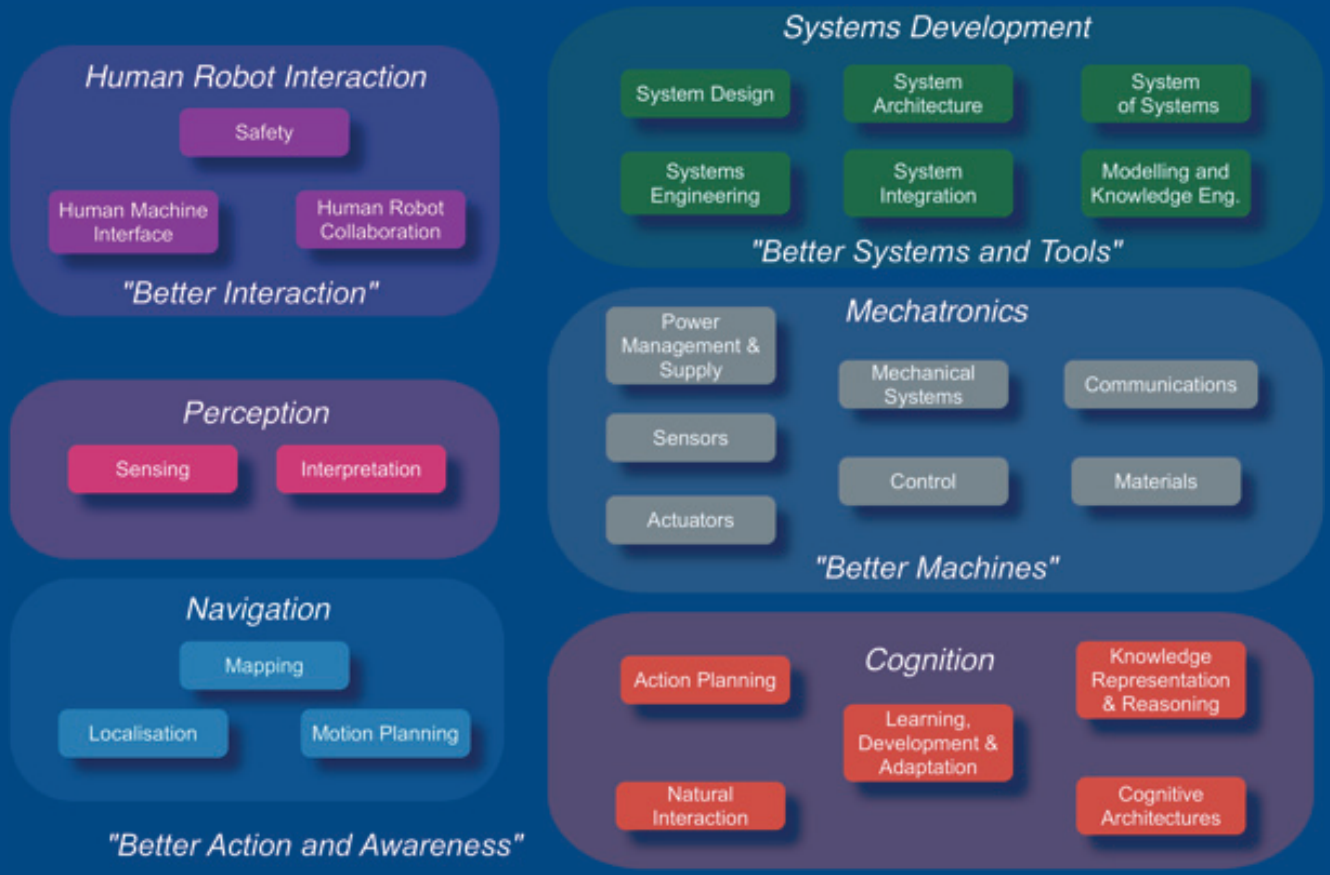
Every robot is built from these core technologies, fundamental improvements in these technologies will impact on all robots.

To Improve Human Robot Interaction. Better Collaboration:

Advanced robots will directly interact with users, physically and cognitively, these technologies will define our experience of robots and shape emerging applications.

To Improve Robot Autonomy: Better Action And Awareness:

Robots will increasingly operate without direct user control. This requires an understanding and interpretation of the environment around the robot by the robot. Technologies in this cluster make robots smarter.



Improving Designs and Systems: “Better Systems and Tools”

As the processes required to develop robots become established the development and analysis of those processes becomes more important. This collection of technologies, collectively referred to as “Systems Design”, relate to design process and the overall design of robots. It is well understood that saving time and cost during the development of a new product is most easily done during the early parts of the development cycle. Tools, processes, and design systems can all help to streamline development. Investment in these technologies is critical to the timely development of products and services and a key enabling factor in the stimulation of a viable robot industry.

System Design

Design covers all aspects of a system from assessing the function to be performed, the way that users will interact with the robot and the analysis of the task. Special purpose tools and methods are applied.

State of the Art

Conventional product design methods are applied to robotics. Special purpose simulation tools are used to assess high level function. Few autonomous mass market products exist and so common system design methods have not yet been established.

2020 Target

To develop robot specific design methodologies, to be able to assess and build in safety and to understand how to design dependable systems that incorporate autonomy. To extend the reach of Open Design methods and integrate system verification with design.

Systems Engineering

Systems Engineering is an interdisciplinary approach which provides strategies, procedures and tools for designing and managing complex engineering projects. It aims at optimising design, cost and function across a system. One of its key concepts is to consider a complex system as a system of interdependent modules. Systems Engineering is of utmost importance for robotics as robots typically are complex systems combining a diverse range of technologies.

State of the Art

Use of a wide variety of Systems Engineering methods and tools in mechatronic design for robotics is well understood and widely used. Historically automotive, space and defence industries have been key drivers for these technologies. Service robotics has yet to fully utilise the benefits of Systems Engineering.

2020 Target

To develop Systems Engineering tools specific to the design of autonomous and semi-autonomous robots, in particular addressing the integration and deployment of whole systems composed of multiple robots, and the interaction between system and environment. Ensure best practice in the wider systems engineering community is rapidly absorbed into the robotics community through collaboration and to act as a driver for system engineering tool development.

Better Systems and Tools...

System Architecture

How a robot system is constructed determines how well it functions. Understanding how the architecture of a robot system affects the overall function of the robot is critical to successfully controlling performance. In this context robot architecture consists of structural (component), behavioural (dynamic) and framework elements that interact and interdepend on each other.

State of the Art

A wide variety of bespoke system architectures are used at present, some commonality with research platforms has been achieved with open source software and common platforms. Widely adopted architectural standards are required coupled to well founded component and behavioural designs.

2020 Target

To define interfaces and common architectures, which are critical to the success of a component supply chain, both in terms of hardware and software components. To have established architectures for distributed planning and control. To establish design patterns and common terminology in wide use.

Systems Integration

Robotic systems are complex combinations of various technologies. Integrating these together requires its own technology. The dependability and operational success of a robotic system will critically depend on the success of its integration into a whole. Integration issues are a key factor in streamlining time to market and in controlling costs.

State of the Art

Tools and processes are commonly employed to aid systems integration particularly in industrial robotics. System integration technologies are also applied in larger scale service robotic applications.

2020 Target

Wide spread use of system integration tools across all sectors of robotics. Processes for design lead integration well understood in all areas of robot design. Improved tools for hardware software integration and deployment.

Technology

State of the Art

2020 Target

Modelling and Knowledge Engineering

Models are used in a variety of different robot system components to encapsulate knowledge. This knowledge may be fixed relative to the task, or may be acquired while performing a task. The knowledge may be designed in or learned. The model and knowledge it encapsulates are moulded together since the model structure depends on the representation of the knowledge. While this is a current research topic and is closely related to other technologies, it is a key technology in all robotic systems.

State of the Art

The use of fixed externally generated models within robotics is well understood. The development of systems able to acquire knowledge in limited environments is within the research domain. There is a good theoretical understanding of the relationship between models and knowledge engineering.

2020 Target

To develop methods and tools to integrate and map knowledge from different domains, and to share knowledge between robots. To develop methods ant tools to transform different abstractions of models using additional domain or application specific knowledge. To develop meta-models and tools for knowledge representation that are specific to robotics.

System of Systems

The study of system of systems is broader than the robotics domain but highly applicable to aspects of it. Complex tasks in unknown environments often involve multiple actors, and combinations of types of actor, static systems, robots, people, organisations etc. System of Systems approaches encompass design, systems engineering and analysis in an integrated manner to explore the engineering of system of systems.

State of the Art

There is extensive research interest in the analysis and application of system of systems approaches.

2020 Target

To establish methods and techniques applicable to robotics. To impact on design and engineering processes to account for system of systems effects such as emergent behaviours.

Technology

State of the Art

2020 Target

Making Better Robot Machines: “Better Machines”

The close coupling of control, mechanism, sensors and actuation is the cornerstone of robotics. This group of technologies are critical to the functioning of every robot. A large proportion of the core innovation in robotics lies within this technical group which can be collectively referred to as “Mechatronics”.

These technologies are the most mature. They pervade academic and industrial settings. Significant developments or improvements in these technologies has a wide impact across all sectors of the community. Step changes in capability are likely to result in observable product steps and impact across markets and enhance competitiveness.

Mechanical Systems

Many different types of robot depend on complex mechanical structures to perform their tasks. Walking machines able to traverse rough or icy ground, micro-manipulators used in surgery robots, or robots able to respond to an elderly person falling all require specially designed mechanical systems.

State of the Art

Compliant systems and systems depending on dynamic control have been developed in research laboratories. Energy efficient mechanisms are at an experimental stage. Traditional mechanical design processes and mechanisms are widely used.

2020 Target

To exploit the integration of sensing and control directly into mechanical structures. To improve force and displacement sensing to provide multi-variate signals at each mechanical joint. To exploit nano-materials as integrated sensors. To exploit new materials in the design of lightweight low cost systems. To develop micro scale integrated manipulators. To develop large scale mechanical systems for construction and decommissioning. To improve mechanical efficiency and reduce energy consumption.

Better Machines...

Sensors

What sets robots apart from other types of machine is their ability to sense their environment. Sensing in 3D, sensing fine movements in a mechanical joint, or providing a sense of taste and smell all require novel sensors.

State of the Art

Vision sensing has become commoditised. Low cost 3D sensors are available. Micro scale mechanical sensors and gyros are now low cost items.

2020 Target

To integrate robotic specific sensor processing at the sensor. To increase the resolution and range of 3D sensors. To exploit novel sensing mechanisms, and multi-modal sensing. To develop broad spectrum sensing technologies. To extend working ranges to different natural environments (e.g. all-weather, tem-

Actuators

A principle function of robots is to interact with the physical world. Actuators provide this motive force. The rage of robot operation means that actuators must be individually designed to meet a wide range of electro-mechanical requirements. From large manipulators able to lift a car, to the high precision actuation used in surgical robots, actuators must be able to meet the demands of continuous dynamic use.

State of the Art

Actuator development is relatively mature as a core element in every robot. Electrical motors provide the motive force in the majority of actuators. Hydraulic and pneumatic and piezoelectric actuation are well understood. Novel actuators based on electro-active polymers and on bio materials are at an experimental stage.

2020 Target

Incremental improvement in power to weight ratios and energy efficiency are to be expected. Novel actuation technology and the employment of new materials are expected to yield new opportunities. Fine scale actuation, particularly in surgical applications is likely to be a major growth area.

Power Supply and Management

Robots will need to be able to operate for long periods without access to a source of power. Managing their stored energy, designing systems that have low energy requirements and managing the use of energy are key to extending the working time of each robot.

State of the Art

Systems design increasingly employs multiple power domains and allows for their management. Energy storage relies on conventional battery systems, or in rare cases on on-board electrical generation. Experimentation with electrical generation from bio-mass is being carried out.

2020 Target

To increase system level efficiencies to reduce power requirements through improved design and systems engineering. To improve the storage and recovery of power from mechanical systems. To investigate alternative power sources and track these trends in other industrial sectors.

Communications

Robots will need to communicate, with each other, with internet based services in the “cloud” and to the “internet of things” around them. Internal module to module communication is also important. As robots become increasingly networked new extensions to existing protocols will be required to account for the types of information robots need to communicate.

State of the Art

Robots use a wide variety of existing communication protocols and methods. Some specific industrial protocols are used in factory automation.

2020 Target

To provide secure communication on mobile platforms both between platforms and to wide area systems. To integrate autonomous transport with new automotive standards for both in-car, car to car and car to road systems. The accommodation of robot requirements into widely used communication protocols.To integrate heterogeneous communication systems to improve data integrity and coverage.

Better Machines...

Materials

Materials often underpin new developments in robotics, from the creation of novel sensors, to lighter mechanical structures and drive mechanisms.

State of the Art

Typically robots use conventional materials and processes for forming and shaping components. Additive manufacturing is used extensively in the development of robots. Research is being carried out to exploit the properties of novel materials in a number of robotic domains.

2020 Target

To exploit new materials that can enhance the design of robots, though improved sensing, mechanical systems or manufacturing processes. To understand and begin to influence the materials science community into seeing robotics, particularly medical robotics, as a new growth area in need of new materials to solve complex

Control

Novel and efficient actuators connected to complex mechanical structures require sensory feedback control methods to ensure that motion is fast, accurate, stable, and repeatable. Controllers that limit the impact of contact with the environment and cause the robot to re-

State of the Art

Position, velocity, and force control are well known. Control issues in systems that amplify movement or force are well understood. Compliant control is mature in a research environment.

2020 Target

To devise safe control strategies allowing for physical interaction between human and robot, including wearable exoskeletons. To devise self-calibrating controllers that adapt to the task. To achieve a closer integration of the reactive (feedback) and deliberative (planning) parts in the control architecture. To develop fault-tolerant and resilient control methods. To control highly redundant robots. To develop more responsive and faster control loops.

Human Robot Interaction: “Better Interaction”

Advanced robots will increasingly interact with people. Physical and cognitive interactions are are at the core of many new areas of robot application. Robots will become tools used by people. Interaction will shift from computer like interfaces to being direct and physical. Robots collaborating and co-working with people both at home and in the workplace will become the norm. These technologies are fundamental to this step change. This increased physical interaction demands higher levels of safety and dependability. These technologies will provide the basis for building safe usable interactive machines.

Human Machine Interface

Robots will increasingly interact with people. This interaction will be essential to the acceptance and integration of robots into our everyday lives. It might be through buttons and a screen, or through physical interaction and gestures. Interaction will move from computer like interfaces to ones based on intuitive interpretation of a user’s intentions.

State of the Art

Touch screen interaction is commonplace, and limited gesture recognition is now available in commercial products. Emotion recognition based on enhanced face recognition is available in the research laboratory, gaze tracking and speech recognition in quiet environments are now commonplace.

2020 Target

To develop instruct-able interfaces. To develop physically interactive interfaces for collaborative working. To develop interfaces that can assess the emotional and cognitive state of the user and respond appropriately. To develop standardised interfaces for autonomous appliances.

Better Interaction...

Human Robot Collaboration

The ability to physically interact with people a fundamental requirement for the next generation of robots. Many potential applications depend on developing safe robots that can provide autonomous, intuitive, physical interaction. To achieve this, human collaboration and safety criteria need to be placed at the centre of the design process. Intuitive physical interaction between humans and robot systems need to be addressed in an interconnected manner. The goal of this technology is to enable the close, safe and dependable physical interaction between people and robots in a shared workspace.

State of the Art

Simple interactions are commonly used, collaboration has been the subject of extensive research. Compliant systems are well understood and commercial products are starting to emerge. Safety standards are starting to emerge.

2020 Target

To develop low cost safe dependable systems able to react and interact with people. To understand the bio-mechanics of human injury and motion. To track, understand and predict human motion, in real-time, in specific environments. To integrate cognition technologies into human robot collaboration. To develop tools for safety validation. To develop safety standards. To develop multi-modal collaboration.

Safety

Robots must be safe to use. Safety is a critically important aspect of robot operation, both in an industrial setting and when robots are interacting closely with people. Safety must be designed into a system, and tested according to well defined standards.

State of the Art

Safety is widely implemented through the exclusion of people from operating environments. In most cases physical barriers ensure a safe operating environment. Safety critical software development processes are used in some areas of robotics. The lack of standardised methods, development tools and verification criteria currently limit reusability.

2020 Target

To develop robust safety based design processes including inherent physical robot safety. Development of standards and methods to verify and certify safety in human robot collaboration. To create software development methods and tools which support the creation of solutions under safety constraints. To create software based safety systems providing dependable failure mode detection and isolation. To develop safety systems for multiple distributed robot systems. To develop predictive systems to assess the safety of human interaction.

Robot Autonomy: “Better Action and Awareness”

Autonomy defines the difference between robots and other machines. The ability to interpret the surrounding environment and alter actions to achieve a goal. Autonomy is built with the underlying technologies that form the machine. It utilises perception technology to extract useful information from sensors to assess the state of the environment. It utilises navigation technologies to assess location, build maps of the immediate and distant environment and move within it. It uses cognition to weld this perception of location and environment together with embedded or learned knowledge about interactions, objects and processes to create and execute plans for action and interaction.

Better Action and Awareness: Perception

This section consists of technologies devoted to the analysis of signals and data provided by sensors. They concentrate on the extraction of knowledge and information from sense data through interpretation of the signals. The ability to extract basic knowledge about the physical environment around a robot is critical to the development of all smart robot applications.

Sensing

If a robot is to correctly understand its environment it must be able to distill useful information from the stream of data produced by its sensors. Transforming and merging this data so that salient information is extracted is a critical step in the process of interpretation.

State of the Art

Raw sensor data processing is often done in a central processing unit. In more advanced applications data is fused from multiple sensors to provide a broader range of information over time. Sensor processing can limit the minimum loop time in dynamic control applications.

2020 Target

To increase the distribution of basic sensor processing closer to the sensors, through increased integration of sensing and processing. To develop techniques to enhance sensor fusion in both non-distributed and distributed systems, and the sharing of sense knowledge between cooperating robots. To standardise sensor interfaces to enable a viable component market place. To perform all-weather sensing in the natural environment.

Interpretation

Robots need to interpret and perceive the objects and features in their environment based on the information extracted from their sensors. Recognising objects, knowing where to grasp an object, or where to place it. Noticing that something important has happened against a background of other events. These skills are essential for a robot to carry out tasks where it must operate in an everyday environment in conjunction with people.

State of the Art

Recognising a handful of objects in constrained circumstances is well known and applied in research systems. The recognition of faces, hands and body pose is well understood and commercial systems are available. The recognition of gestures and to a lesser extent facial expressions is beginning to be exploited. The interpretation of 3D and visual sensory data is well known for the identification and recognition of salient features in an environment. The extraction of shape and 3D reconstruction from vision sensing is being researched with some success.

2020 Target

To be able to reliably recognise a wide range of known objects. To be able to reconstruct 3D object shapes from sensor data to allow fast and efficient grasp planning and visual servoing. To exploit the potential for facial expression recognition, to be able to recognise and interpret complex gestures. To provide reliable salient point and situation recognition over wide scale ranges.

Better Action and Awareness: Navigation

Robots need to navigate through their operating environments avoiding obstacles and reaching their destinations. This requires an interacting combination of different technologies in order for the robot to know its location in its environment and plan its navigation.

Mapping

For a robot to understand the wider environment it must construct maps as it travels through that environment. These maps may carry markers for points of interest. Robots, and particularly, mobile robots have no absolute point of reference so maps must be constructed from the environment and continually verified. If a robot retains these maps for use over a long time scale then as the environment changes it will need to keep these maps up to date.

State of the Art

The derivation of maps from sensor data in unknown environments is now well understood. Loop closing in large sensor derived maps is also understood.

2020 Target

To be able to maintain maps of dynamic environments over longer periods of time. To be able to segment and apply labels to maps identifying key environmental features. To be able to segment maps based on environmental features in a way that is compatible with the users' segmentation of the environment. To be able to add semantic information to maps. To develop cooperative map forming methods.

Localisation

In order to successfully carry out tasks a robot must know where it is. The accuracy of this localisation will depend on the task. Although outdoors GPS can provide a very accurate idea of location it does not work everywhere. Indoors robots need to use their maps and sensors in combination to identify where they are. When people instruct robots they often need to specify a location in human terms. Robots need to be able to segment spaces and identify locations in a way that is compatible with a users instructions.

State of the Art

Localisation with GPS and augmented GPS systems is well known. Localisation on maps constructed form sense data is well known. Localisation of complex mechanical structures is also well known.

2020 Target

To increase the accuracy of localisation on maps constructed from sense data. To be able to merge and combine multi-scale maps derived from different data sets. To be able to use human like segmentation of maps to locate waypoints and locations identified by an unskilled user. To be able to localise in a dynamic environment. To perform opportunistic localisation by exploiting existing signals in the environment.

Motion Planning

Robots need to plan the path and how they move from one place to another. Complex mechanical systems may have multiple paths to reach a destination but each with a different cost. Speed needs to be traded with stability when carrying a heavy load, a mobile robot needs to plan how to pass through a doorway as smoothly as possible.

State of the Art

Trajectory planning and simple motion planning round obstacles is well understood. Complex motion planning for multiple degrees of freedom arms is well understood as an optimisation problem.

2020 Target

To devise robust strategies for motion planning multiple degrees of freedom mechanical systems in unstructured and dynamic environments. To devise large scale motion planning methods that can succeed with sparse environmental data. To improve distributed cooperation planning in multiple robot systems.

Better Action and Awareness: Cognition

Cognition provides a robot with the ability to understand its environment – even from partial knowledge – now and in the future, and to use this understanding for action. Cognition breaks free of the present in a way that allows the robot to act reliably and safely, to adapt, and to improve. This is needed for robots to act in a goal-directed way in unstructured environments, such as in everyday environments. In such environments, robot tasks can only be incompletely or vaguely specified and the robot must use common sense reasoning to fill in the necessary detail based on the current context and goals.

Many robot technologies exploit cognitive processes and techniques, including perception, planning, navigation, and human-robot interaction. All of these will benefit from improvements of the cognitive technologies listed here.

Cognitive Architectures

A cognitive architecture determines the organisation of the system's cognitive functions. It provides the infrastructure for embedding knowledge, acquiring new knowledge, and using that knowledge to understand the world, to act purposefully, and to anticipate the need for action. It can also provide a framework to allow new skills to be developed through experience.

State of the Art

General-purpose cognitive science architectures such as Soar and ACT-R are well established. Contemporary research in cognitive architectures is increasingly targeted at robot platforms.

2020 Target

To establish standardised, well-engineered, and re-usable cognitive architectures that facilitate integration and sharing of knowledge from disparate sources, including humans, robots, and the internet. To incorporate a developmental capacity for acquiring and honing robot skills, especially those concerned with adaptive and prospective control of actions. To exploit models of embodied cognition. To integrate autonomic processes that cater for self-diagnostic, self-correcting regulation of system performance.

Learning Development and Adaptation

Learning allows the accumulation of knowledge over time to influence the abilities of a robot system, in particular its abilities to perceive the environment, to make decisions, to behave intelligently, and to interact naturally with humans.

State of the Art

Many different types and a broad range of methods of learning are well known and well characterised mathematically. Simple learning of motion sequences is widely used, and adaptive control strategies are used in a variety of complex systems. Categorisation is part of intelligent sensing; learning and generalising cases is a part of planning.

2020 Target

To devise methods for the long term accumulation of information about the environment and the robot's own performance. To learn from single-instance demonstration by an individual person and to have the acquired skill honed through coaching. To learn collectively, both across the experience of multiple robots and from observation of humans and other animals. To uncover innovative ways to addressing problems and dealing with novel situations by generalising learned knowledge and recombining known strategies. To exploit creativity to make robots more natural and entertaining companions.

Knowledge Representation and Reasoning

Knowledge-based methods provide formalisms to represent knowledge in an explicit, machine-readable form, and to reason from this knowledge and about this knowledge. Knowledge is needed for robots to understand the environment, to interact with humans, to plan actions, to share experiences, and to diagnose system faults. Knowledge-based methods allow reasoning from incomplete and uncertain knowledge.

State of the Art

Knowledge Representation and Reasoning (KR&R) is a mature field of Artificial Intelligence, which is pivotal to leading commercial technologies like data mining, search engines and recommendation systems. Many KR&R formalisms and tools are available which target different types of knowledge, e.g., ontological, temporal, causal, procedural or spatial. Some languages produced in this community have become standard, like the OWL family.

2020 Target

To leverage the use of available KR&R methods to allow robots to: understand their environment at the semantic level; cope with partial and inconsistent information; engage in meaningful interactions with humans; easily incorporate new knowledge about novel tasks and domains; and share knowledge and experience with other robots.

Action Planning

Action planning is the exploitation of temporal projection and means-ends reasoning to generate plans for future actions that achieve given goals. This includes task planning, scheduling and observation planning, as well as planning under uncertainty and multi-robot planning. Knowledge and cognition are key components in this process.

State of the Art

Action planning is one of the oldest areas of research in Artificial Intelligence, and many effective planning systems are available. The coupling of action planning with sensing and actuation has been so far mostly the topic of academic research, but it is now reaching a more mature stage. Geometric or motion planning are typically not addressed in this area.

2020 Target

To incorporate advanced action planning techniques into robotic systems in order to meet the demands for increased flexibility, autonomy, safety and ease of programming. To integrate planning in the execution loop to address changing, complex and unpredictable application domains, especially those where robots and human co-exist. To integrate action and motion planning. To enable the automatic synthesis and verification of robot behaviours.

Natural Interaction

Collaborating and interacting with humans and other co-workers requires a high level of cognitive compatibility between human and machine. Successful interaction depends on an understanding of a partner's needs and intentions. In humans, these are conveyed by a variety of cues: words, gestures, and emotional expressions, and rely on systems of turn taking.

State of the Art

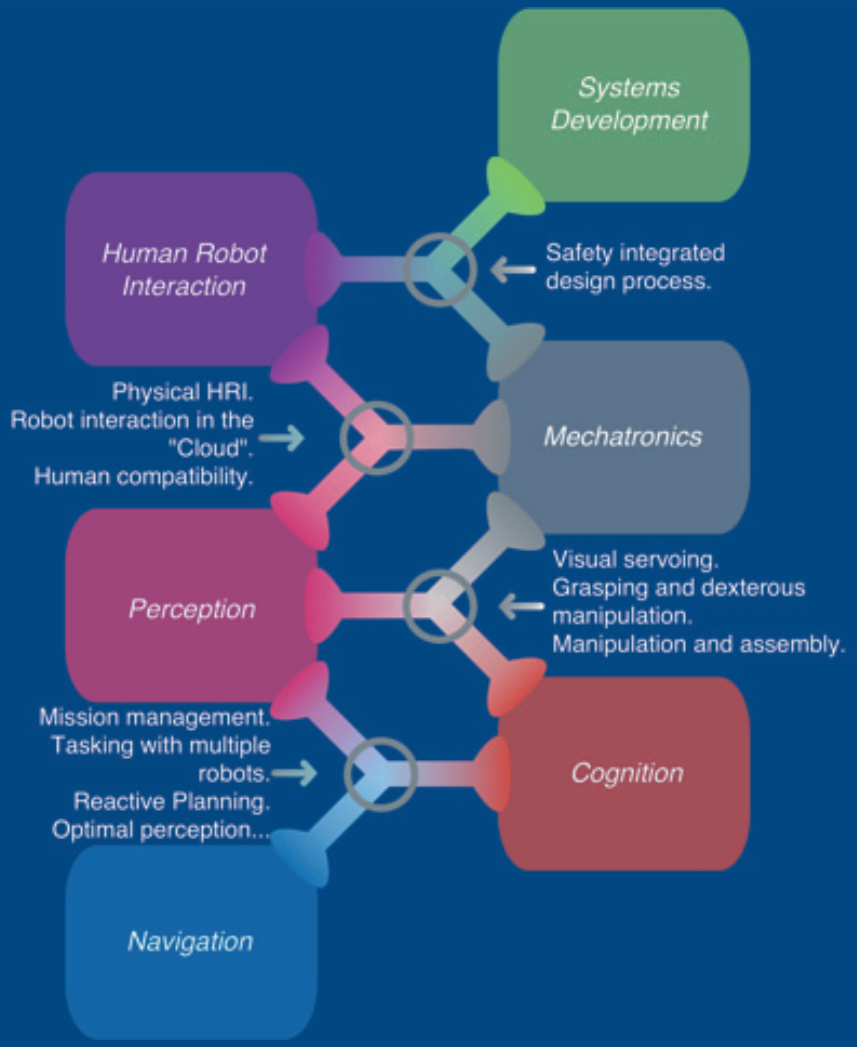
Natural Language Processing (NLP) allows cognitive systems to understand and use ordinary language, making it easier to communicate with inexpert users. Simple interaction is common in commercial systems from search engines to smart phones, including both speech and gesture. Minimal systems for emotion recognition are used in automated support and FAQ systems, often based on keyword recognition.

2020 Target

To extend basic interaction capabilities to exploit gestural, emotional, and intentional cues. To develop system capabilities of limited forms of cooperation and collaboration. To allow robots to take and give instructions. To allow robots to relate language to known perceptual categories, actions or plans such that they can infer intention and understand meaning. To allow systems to detect and intervene when failures of collaboration or understanding occur.

Technology Combinations

Technology combinations represent areas of significant growth and opportunity. Fundamental advances often come from the combination of different underlying technologies that build a performance advantage greater than the sum of its parts. These technology combinations often provide significant "gearing" to step changes in capability.



All too often these cross boundary technologies take a long time to develop because of artificial barriers created by compartmentalised funding and difficulties in cross fertilising expertise. Highlighting cross boundary technologies and the establishment of responsive funding to new developments should enable Europe to capitalise on new advances and gain leverage in newly combined technical areas.

The broad technical base in robotics means that the opportunity to develop technology combinations is already an important part of the robotics technology landscape.

By their very nature technology combinations do not fit easily into any top down classification scheme. Instead they rely on links that bind different strands of technology together. By explicitly considering combinations as an important part of the research and innovation process the structures and support for these technical cross links can be better managed.

Technology combinations will also occur between robotics technology and other global technology strands creating high level and wide spread opportunities for innovation. For example coupling robotics to big data initiatives, to global knowledge engines or the internet of things.

It is important to note that the combinations detailed here are not targeted at specific markets or forms of robot, but combinations that provide step changes in capability across the whole spectrum of robotics application.

These descriptions illustrate a number of different technology combinations.They are examples from a large number of technical combinations that need to be explored. Building on mutual strengths within an open collaborative environment is essential to the exploration of combinations.

Technology combinations can be clustered with respect to the general linkages they create between the high level technical clusters identified earlier. In some of the examples the combinations form within a high level cluster, in others the combination spans between clusters.

Perception, Mechatronic and Cognitive Technologies

Visual servoing

The combination of vision, control and motion planning technologies to drive a mechanical structure from scene information in a visual stream.

Grasping and dexterous manipulation

The combination of tactile sensing, control of a complex mechanical system, and the interpretation of object shape and context. Typically involves carrying out manual tasks such as picking up and orienting irregular objects, and carrying out manipulation of those objects, for example picking up and pushing an electric plug into a socket.

Manipulation and assembly

The manipulation of multiple objects presents significant challenges in the integration of perception, planning and task execution. This combination has broad impact across manufacturing, space and healthcare applications.

Perception, Mechatronic and Human Robot Interaction Technologies

Physical human robot interaction

Combines compliant control of a complex mechanical structure with visual and tactile perception of human interaction to produce intuitive physical interfaces.

Robot interaction with cloud services and ambient devices

Robots need to gather contextual data from their surroundings, other devices, additional data may be available via cloud devices or the internet of things. The interpretation of sense data, features or objects can also be offloaded to the cloud so that global data sources can be used to maximise the information gain.

Bio and human compatible systems for physical interaction

Combines mechanical systems design, materials and sensing with physical human robot interaction technologies to develop robotic systems that are optimal for human interaction. Applicable in rehabilitation, industrial co-working, surgical robotics and assistive technology, when creating close coupled robotic systems.

Mechatronic Technologies

Mobile manipulators.

The integration of multiple degree of freedom mechanical structures, for example a robot arm or pair of arms, mounted on a mobile platform. Combines platform localisation with the control of complex mechanical structures to provide navigation and localisation for end effectors in unknown environments.

Integrated sensing in mechanical joints and links.

Combines multi-axis sensing and materials to integrate force and position sensing directly into mechanical joints linking with their actuation providing a distribution of control at the joint.

Cognition and Human Robot Interaction Technologies

Cognitive human robot interaction

Combines complex control of mechanical structures with interpretation of the collaborating partner's actions and their cognitive contexts with respect to the environment. Also includes mutual interaction with objects in the environment, for example the shared lifting of an object, providing assistance when standing up, or the exchange and use of an object or tool.

Perception, Navigation and Cognition Technologies

Dynamic mission management

Combines cognition, planning and navigation to ensure continuous management of a complex multi-agent system in a in real time dynamic scenario. Applies where multiple robot agents must interact with human resources and static systems to achieve a long term mission.

Task management with multiple independent robot devices

Combines task planning technologies with communications to effect tasks involving multiple independent robots with a common task or mission. Applications in agriculture, manufacturing, inspection and maintenance tasks.

Reactive planning

Combines perception of a robot's dynamic environment and its interpretation, with planning, localisation and navigation technologies to provide responses to task and mission plans as the local environment changes in unexpected ways. Applicable to multiple application areas from smart industrial robots to marine and aerial systems operating in unstructured environments.

Optimal perception for obstacle detection

The dynamic motion of sensors to maximise the information returned requires an integration of interpretation and planning systems that have task awareness. Where sensors are fixed then platform motion and trajectory need to be similarly planned to maximise the detection of obstacles. Where multi-modal sensing, e.g. Visual and tactile is used planning is needed to adapt motion to optimise information gathering.

Navigation Technologies

Simultaneous Localisation and Mapping (SLAM)

The combination of map-building and localisation carried out in the same time frame. Providing localisation and orientation information extracted from unknown environments to build a map that can be used to navigate the discovered space.

Systems Development Technologies

Model driven engineering of complex systems

Providing an integration between models, knowledge representation and systems engineering to the robot designer allowing a framework for building up complex systems from predefined components and sub-systems. A rapid development strategy able to speed time to evaluation.

Systems Development, Mechatronics and Human Robot Interaction Technologies

Safety integrated design process

Combining systems engineering and safety engineering to provide mechanical systems with guaranteed safety properties based on sensor input that observes the environment. Through integrating the safety engineering with the design process and sensor placement and processing, a whole system approach to safety has the potential to provide guaranteed levels of system safety.

Technology Assessment

Making effective progress in the development of technologies critically depends on knowing the state of the art and knowing the impact of particular levels of capability. By assessing capability and benchmarking progress over time triggers can be set in place to enable timely technology transfer and exploitation.

There will be new technologies generated in the coming decade, identifying and supporting them is a priority, however most of the basic technologies required to make effective and functional robots already exist. A key part of the technology strategy presented in this document is establishing the support required to bring technologies forward to market. This strategy addresses both the technologies that need technology transfer support as well as those that are not yet well developed enough to be commercialised.

By focusing on levels of capability coupled to improving levels of deployability progress can be optimised.

Capabilities

Pre-commercial technologies require investment in research to raise capability levels to the point where the technology transfer has value. The first part of this process is the identification of these pre-commercial technologies, the second is the identification of the capability levels needed in any particular domain for that technology to have transfer value. Establishing current and future capability levels is key to this identification and support process.

For those technologies that have found application there is often a need to work with and stimulate the research

community to improve efficiencies, improve implementation strategies, or adopt new underlying technical and scientific advances that can provide higher levels of capability.

In all these cases the identification of capabilities, and any associated metrics, is key to both measuring progress and establishing targets for achievement. For industry this provides an indication of the feasibility of proposed products and services, reducing risk. For the academic community it sets clear targets where technology transfer opportunities exist. By aligning the two parts of the community, where this is practical, it is expected that this will result in higher and more effective levels of technology transfer.

Benchmarks

In order to be able to prioritise investment in technology it is important to be able to firstly identify technology barriers to market and secondly to be able to measure progress as technologies develop.

Benchmarks provide a mechanism for assessing the state of the art and for measuring progress.

They provide an indirect means of assessing the impact of funding. They also allow the technical capability within Europe to be reviewed and global comparisons made. In order to make these assessments it is important to have a process for establishing the current state of the art for each of the technologies.

The Multi-Annual Roadmap document provides further details of both capability assessment and technology benchmarking.

Goals and Targets

6

Research and Innovation Strategy

Outlines the goal of developing a strong European market in products and services through successful research and its acceleration to market. Examines scope and priority setting and science based research.

Impacts

Overview of the impact of product visions and the importance of the service and infrastructure needed to support the long term deployment of each.

Key Performance Indicators

Overview of the Key Performance Indicators used to measure market impact and progress towards objectives.

Key Targets

A statement of goals and targets designed to create a successful European robotics marketplace.

Market Goals

Market goals for Europe based on current performance levels to help illustrate the growing impact of robotics on European strategic goals and competitiveness.

Research and Innovation Strategy

The creation of new markets and the creation of wealth and jobs depend on the generation and management of relevant Intellectual Property. The generation of Intellectual Property depends on the right intellectual and financial investment in innovation.

Developments in technology capability drive innovation. The increase in ability of a particular technology to achieve a higher performance level, a new method, a new manufacturing process; all of these directly lead to new products, new opportunities and new markets. Investment in research, in world class research establishments, in highly trained graduates, is the only way for Europe to maintain and increase its share of the robotics technology market.

Even with this backing innovation requires risk taking and inspiration, but in particular it requires the ability to recognise the potential of a good idea and sufficient investment to allow it to be nurtured and exploited. It is essential that Europe creates an environment where this becomes the norm: Where academics understand the potential needs of industry and understand how to deliver their ideas, where industry understands the limitations of academic research and can support the process of technology transfer, being prepared to take the risk.

Much can be done to support the growth of this innovation culture, to support open design and collaboration, to channel the flow of ideas into the creation of IP that makes markets. In order for Europe to create a global lead it must also promote this flow of innovation so that it is timely and effective, time to market, early acquisition

of key IP and early phase investment bridging the so called "valley of death" are crucial to Europe's success.

Building systems that support excellent research; Actively joining partners to create projects that have viable commercial results; building systems that support the flow of talent from academia to industry, and which allow industry to experience academia. Building a shared understanding is critical to success.

Scope

The scope of Research Development and Innovation strategy is therefore framed by the range of technologies that underpin the development of robotic systems and the markets impacted by robotics technology.

The strategy must address the need to maximise the impact of robotics technology on the key European economies, create and grow a strong European R&D&I infrastructure including support for the long timescale research and development.

The strategy must also address the market both from a commercial perspective and from a end user perspective, encompassing supply and value chains as well as legal ethical and societal issues.

The scope of robotics strategy in europe is detailed in the Multi-Annual Roadmap which also identifies areas of key research, development and innovation priority.

Priorities

This dynamic technical environment militates against a static system of technical priorities and in favour of the construction of mechanisms able to identify enduring trends and technical step changes with significant impact.

The key high level research priorities are therefore driven by the following needs:

- To develop technologies and capabilities that will underpin a world-leading competitive position of the industry.
- To provide systems able to contribute to the major economic and societal challenges.
- To establish, within Europe, world leading capability on all key robotic technology areas.
- To build strong links between academia and industry and to exploit those links to their full potential.
- To enable the design and deployment of robot based products through improved design and development systems.

In assessing these priorities it is also essential to establish mechanisms for the review of research and market trends in order to regularly re-evaluate priorities.

Science based research

Robotics has a key, and unique, contribution to excellence in science. Cognitive and biologically-inspired robots present one of the greatest challenges for integration science and the understanding of systems of systems. Not only do cognitive robots require leading-edge solutions in many traditional disciplines (be they engineering, computer science, control, power systems, electronics, mathematics, communications, materials, cognitive psychology, neuropsychology, biological system, sociology, law, ethics, etc.) but the innovative drive comes from developments

at the boundaries, making this a truly multi-disciplinary approach. Add to this the complexity of robotic systems and the fact that they have to act robustly in the real world as part of larger systems and it is clear that the challenge is both at the level of multi-disciplinary science and the development of an integration science that develops a framework of understanding to account for the synergistic interactions between complex systems, each with their foundations in different theoretical traditions.

Robotics not only strongly depends on scientific input from many other fields, as illustrated above, but also influences and challenges many other areas of science including biology, neuroscience, medicine, and cognitive science. In these areas robotics provides an opportunity to create new experiments, build interactive models and test theories in ways that were previously difficult or impossible.

Impacts

Robot technology has the potential to impact on a wide range of different market domains and industries. It is likely that the full extent of this impact will materialise over several decades. There is wide acknowledgement that this impact is already growing and that it is essential for Europe to stay ahead of the wave. Measuring and monitoring this growing impact is a critical part of the process that will shape future strategy.

There are key areas of activity within Europe that will provide indications of the level of impact:

- Increased take-up of product capable robotics technologies in both existing and new markets.
- A rising of awareness across the community about what robotics can achieve.
- Increased European-focused standardisation activities.
- Increasing interest from the European and worldwide investment communities.
- Observable robust and efficient supply chain development.
- Increasing evidence of efficient academic and industrial collaboration.
- Wider community based impacts can be observed through the following:
- An positive economic impact on the competitiveness and growth of industries deploying robotics technology.
- An positive economic impact on the competitiveness and growth of the European robotics industry, and a consequential knock-on effect in the global robotics market.
- Increased European job creation and job protection.
- An observable contribution to solutions for Europe's societal challenges.

Assessing the domain impact of robotics technology will vary with application domain. In some domains robots will be the only viable solution to particular problems, in these domains the impact of robotics will be easier to assess because robotics is more likely to have a visible transformative effect. In many other domains the impact of robotics will only be felt when their application reduces costs or increases service levels for equivalent cost, this scenario is typical of the mass market sectors. In other domains robots may simply be a device of choice providing additional benefits at additional cost. Any overall analysis of impacts will need to take these different modalities of impact into account.

From the wider perspective robots have the potential to transform manufacturing and service delivery and thus impact on European citizens. It is important to examine and assess this impact to ensure that societal and ethical goals are being met. In manufacturing the potential for competitively producing goods in Europe against markets with a lower cost base can be assessed through industrial output. The increased ease of use and flexibility available from smart industrial robots will impact on small and medium volume manufacturers allowing them to compete in new markets and grow. It will be important to monitor this trend and make global comparisons. Contrary to popular belief there is every indication that in the economy as a whole the widespread use of robots in production will increase overall employment and grow the economy. This highly desirable impact will take time to establish but it is an important benefit.

The end user impact of the SRA will take time to have an effect, research stimulus will take time to result in improved products and services to users and consumers. However the implementation of a European agenda will ensure that Europe maintains its competitiveness and gains significant IP and develops a well trained workforce able to adapt and understand this new robotic era. Establishing metrics to evaluate these trends will be part of the ongoing process of monitoring and updating that will follow the publishing of the SRA.

A well thought out innovation policy and its careful implementation will ensure that SMEs have the ability grow to midscale companies, and that ideas are effectively transferred from academic laboratory to industrial manufacturing. The gearing effect of investment in innovation is clearly understood, the impact of a well structured policy should be seen in the generation of new startups and the stimulation of technology transfer.

Key Performance Indicators

Measuring the impact of R&D&I initiatives and the performance of the industry is an important part of this strategy. Identifying measurable indicators and tracking them over time will give clear indications of progress towards strategic goals.

There are a number of key performance indicators that can be used to measure progress and impact. These can be characterised as follows:

- Number of researchers and technology developers engaged in industry, academia, and research organisations on robotics or robotics related R&D&I activity.
- Realistic awareness amongst policy makers, public and industry of robotics potential, and PR-related effects on users and users' attitudes towards robots.
- Overall public awareness of robots and robotics issues.
- Visibility, credibility and acceptance of robotics and outputs from R&D&I activity by target groups.
- Level of penetration of robotics into key industries and services benchmarked internationally.
- Size and growth of the European robotics industry as market shares per domain.
- Level of participation in R&D&I programmes by both commercial organisations (including SME) and academia.
- Number of successful products and services launched using technology developed as a result of this R&D&I activity.
- Number of companies feeding the supply chain.

- Number of robotics and related start-ups created in Europe.
- Amount of private capital and loans invested.
- Success rate of funded projects in terms of market impact.
- Growth rate of organisations participating in SPARC.
- Number of relevant European patents generated, benchmarked internationally.
- Number of deployed systems in each sector (as far as European data can be obtained).
- Robotics and related SME growth rates.
- Numbers of applications to the near market instruments and their application spread.

As robotics deployment spreads the indirect impacts on efficiency and service delivery will need to be assessed. These are the impacts that will have the broadest effect in establishing confidence in the robotics industry. There will be an impact on processes as work practices change to accommodate robots, there will be an impact on infrastructure as systems and modes of operation shift to balance the efficiencies gained through implementing robot technology. People will alter their patterns of work and leisure to match the benefits of robotics. These indirect impacts are likely to be felt before they can be measured.

Although these longer term wider impacts will be harder to measure, by 2020 the trends should be visible. In healthcare provision, logistics, agriculture and small scale manufacturing the efficiency and service gains should be noticeable. In logistics and civil applications the increasing presence of robotics technology will be taken for granted, ubiquitous and effective in a wide range of different detailed tasks. The main indication of impact will be in Europe maintaining and growing a strong foothold in the global robotics market and the development of a strong robotics sector within Europe.

Key Targets

These are the targets against which the impact of this SRA and the effectiveness of its implementation will be judged.

- Identify key technologies in each domain that have been developed to enable new markets.
- That there is a well planned innovation strategy and that it is supported.
- That there are clear access points to information about the robotics community in Europe.
- The adoption of robotics technology has been strongly promoted.
- That policy makers understand the importance of Robotics and its potential impact.
- That the European robotics market has a significant a global reach.
- That the challenges raised by Legal Ethical and Societal issues are being addressed.
- That education and training in the skills needed for Robotics are being fully developed.
- That collaboration and dialogue between all elements of the wider robotics community is effective.
- That technology transfer is actively supported and enabled.
- That an environment in which SMEs can flourish has been created.
- That standardisation and the development of a robust supply chain is being promoted.
- That Europe's Universities and Institutions generate and propagate world class robotics research.
- The establishment of cross sector engagement to strengthen and promote the uptake of robotics technology.

The vision this SRA presents will only become a reality if there is financial and intellectual investment and if governments create supportive frameworks both for innovation and the deployment of robotics technology. The year 2020 will mark a point where the major players are defined and the market will be geared for growth.

These markets will be shaped by agile organisations, often SMEs, owning key parts of the technology jigsaw. Early collaboration and astute intellectual property acquisition will help build viable enterprises that will ultimately dominate individual markets and supply chains. The market also depends on major existing market leaders understanding and realising the market opportunity offered by robotics technology.

This SRA should 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.

Traditional dividing lines will disappear and new opportunities will emerge. Europe's robotics industry must be ready to rise to the challenge.

Market Goals

- To contribute to the Europe 2020 goal of returning the percentage of value added manufacturing to 20% of GDP.
- Europe must exploit a significant fraction of the IP it generates to its own advantage.
- Europe must maintain its global position in industrial robotics and extend it to cover the emerging smart manufacturing sector.
- Europe must win a significant fraction of new markets.
- Contribute to a growth in the European robotics industry resulting in the creation of:
  - ➡ more than 75,000 new qualified jobs at European manufacturers of industrial and service robots;
  - ➡ more than 30,000 additional new high-tech jobs in European companies supplying components and software for robots;
  - ➡ more than 30,000 additional new high-tech jobs in European companies supplying components and software for robots;
  - ➡ more than 140 new European companies as spin-offs from research and university institutions;
  - ➡ more than 140,000 new jobs in European service industries using a broad variety of service robots and taking advantage of the increased productivity;
  - ➡ an expected robotics-related increase of the EU-27 GDP by €80bn.

The community has also set the following targets to be achieved by 2020:

- A 35% stake of the estimated €43bn industrial robot market.
- A 65% stake of the estimated €16bn professional service robot market
- A 20% stake of the estimated €2.4bn domestic robot market.

Strategic Research Agenda For Robotics in Europe 2014-2020

SPARC

The Partnership for Robotics in Europe