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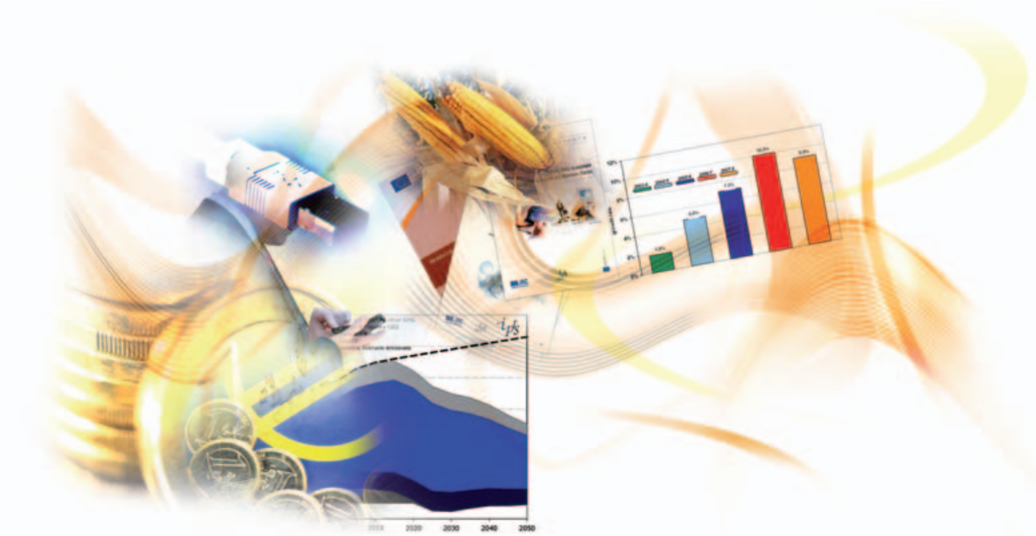
A Helping Hand for Europe:
The Competitive Outlook for the EU Robotics Industry

Authors: Simon Forge and Colin Blackman

Editors: Marc Bogdanowicz and Paul Desruelle



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The mission of the JRC-IPTS is to provide customer-driven support to the EU policy-making process by developing science-based responses to policy challenges that have both a socio-economic as well as a scientific/technological dimension.

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Preface

Information and Communication Technology (ICT) markets are exposed to more rapid cycles of innovation and obsolescence than most other industries. As a consequence, if the European ICT sector is to remain competitive, it must sustain rapid innovation cycles and pay attention to emerging and potentially disruptive technologies. In this context, the Directorate-General for Enterprise and Industry (DG ENTR) and the Institute for Prospective Technological Studies (JRC-IPTS)[1] have launched a series of studies to analyse prospects of success for European ICT industries in the face of technological and market innovations.[2] These studies, under the common acronym "COMPLETE",[3] aim to gain a better understanding of the ICT areas in which it would be important for the EU industry to remain, or become, competitive in the near future, and to assess the likely conditions for success.

Each of the "emerging" technologies (or families of technologies) selected for study are expected to have a potential disruptive impact on business models and market structures. By their nature, such impacts generate a moving target and, as a result, classical well-established methodologies cannot be used to define, observe, measure and assess the situation and its potential evolution. The prospective dimension of each study is an intrinsic challenge that has to be solved on a case-by-case basis, using a mix of techniques to establish lead-market data through desk research, expert group discussions, company case analysis and market database construction. These are then combined with reflection on ways and means to assess future competitiveness of the corresponding industries. This process has resulted in reports that are uniquely important for policy-makers.

Each of the COMPLETE studies illustrates in its own right that European companies are active on many fronts of emerging and disruptive ICT technologies and are supplying the market with relevant products and services. Nevertheless, the studies also show that the creation and growth of high tech companies is still very complex and difficult in Europe, and too many economic opportunities seem to escape European initiatives and ownership. COMPLETE helps to illustrate some of the difficulties experienced in different segments of the ICT industry and by growing potential global players. Hopefully, COMPLETE will contribute to a better understanding of the opportunities and help shape better market conditions (financial, labour and product markets) to sustain European competitiveness and economic growth.

This report reflects the findings of the JRC-IPTS COMPLETE study on robotics applications in general, and in two specific areas selected because of potential market and EU capability in these areas: robotics applications in SMEs, and robotics safety. The report starts by introducing the state of the art in robotics, their applications, market size, value chains and disruptive potential of emerging robotics technologies. For each of the two specific areas, the report describes the EU landscape, potential market, benefits, difficulties, and how these might be overcome. The last chapter draws together the findings of the study, to consider EU competitiveness in robotics, opportunities and policy implications. The work is based on desk

1 IPTS is one of the seven research institutes of the European Commission's Joint Research Centre (JRC).
2 This report is one out of a series, part of the umbrella multiannual project COMPLETE, co-financed by DG ENTR and JRC/IPTS for the period 2007-2010 (Administrative Arrangement ref. 30667-2007-07//SI2.472632).
3 Competitiveness by Leveraging Emerging Technologies Economically. For more information on the COMPLETE studies, see: http://is.ec.europa.eu/pages/ISG/COMPLETE.html

research and targeted interviews with industry experts in Europe and beyond. The results were reviewed by experts and in a dedicated workshop.

The report indicates that, while the EU robotics industry has in the past benefited from a strong automotive industry market, the market for conventional industrial robotics for large-scale automated manufacturing is becoming saturated, with limited room for future growth. Potential new market directions for the EU robotics industry include applications in different industry sectors (e.g., food processing, health care) and new application segments within those sectors (e.g., new medical applications). The report underlines that in manufacturing SMEs, robots could be used as a 'third hand' in many jobs. Although safety has always been important to the robotics industry, the report emphasizes that ensuring user safety becomes crucial when robots work in close interaction with humans, in service or industrial applications. The study found that the EU has an early lead over other regions in the safety area, as important conceptual and more technical research has been undertaken through EU Framework Programme R&D projects. To ensure that the EU is in a position to build on its strengths and capitalise on the opportunities now emerging, the report recommends a holistic approach to support the development of a robot 'eco-system', addressing both the demand side and the supply industry. The report ends by providing a list of key policy recommendations aiming to support competitiveness of the EU robotics industry.

David Broster
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JRC IPTS

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Note: The study's Interim Report is available as a separate Annex and can be downloaded from: http://is.jrc.ec.europa.eu/pages/ISG/COMPLETE/robotics/index.html

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Executive Summary

This report explores the state of the art in robotics and assesses the prospects for the European Union's robotics sector to capitalise on the market opportunities that are now appearing. It seeks to understand whether recent technological advances are such that they will disrupt the present market and offer new opportunities for the EU, or whether the sector will stagnate because of its dependence on saturated, traditional mass manufacturing.

The history of what is today's robotics industry in the EU goes back to the 1970s, when the first large-scale applications of machines that could be called robots were perfected for the automation of car factories. A thriving robotics industry emerged to provide the manufacturing sector with flexible and programmable machines for complex repetitive tasks, usually on high-volume production lines.

However, the market for conventional industrial robotics today is becoming saturated. In consequence, the robotics industry is looking for new opportunities to assure its future. For instance, researchers worldwide have been pursuing the goal of humanoid robots, potentially useful as domestic household servants, carers and helpers. Several of Japan's leading consumer technology companies (e.g. Honda, Fujitsu, and Sony) have invested significantly in this quest. Yet in reality, robots as domestic servants are still at an early research phase. A robot with sufficiently full functionality and the safety characteristics to mix usefully in close proximity with people as a domestic servant has yet to be industrialised.

Nevertheless, over the past thirty years, significant progress has been made in other novel applications for robotics. For instance, military robotics has developed a wide range of guided robots, e.g. for bomb disposal, and unmanned aerial vehicles capable of autonomous behaviour to reach their target. Other developments have been made in the medical field, (e.g. surgical robots), in fields such as agriculture and food processing (e.g. milking robots) and in oil and gas (e.g. subsea robot vehicles for offshore recovery).

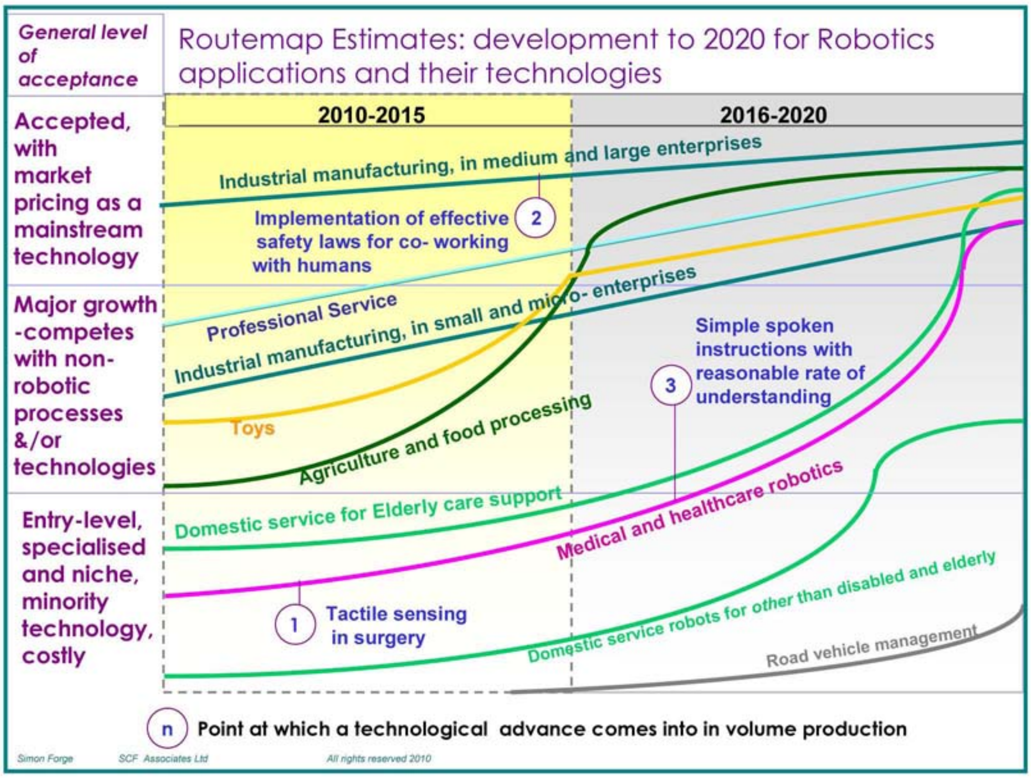
Another example of a future opportunity could be wider take up of robots by small and medium-sized enterprises (SMEs), significant economically in the EU as they form over 99% of all companies.[4] There are more than 2.3 million industrial manufacturing SMEs in the EU. Enhancing their productivity could greatly augment the EU's overall global competitiveness, creating new jobs and re-invigorating the EU's industrial sector.

The EU already has considerable technical and commercial competence across these innovative areas of robotics which could now be refocused on these new markets, in for example, food processing, professional services, medical, care and domestic service markets, including co-working robots. The timeframe for significant market penetration in these different sub-sectors varies from five to twenty years or more.

An outline is given below of development for the major future market segments expected in robotics, by application. Figure 1 depicts trajectories of evolution for each key segment across the levels of acceptance, from entry level to mainstream, via the major growth phase.

4 Source: Eurostat's portal on SMEs:
http://epp.eurostat.ec.europa.eu/portal/page/portal/european_business/special_sbs_topics/small_medium_sized_enterprises_SMEs

Figure 1: Comparing the emerging branches of the industry - a route map for development



Moreover, techno-economic analysis indicates that the robotics industry may be at a turning point. At a technical level, the intelligence available in silicon has reached a threshold of capacity and cost that enormously increases the functionality for comprehension of scenes, cognitive processing to understand spoken commands and fine control of manipulators. Sensors are more sophisticated and reliable with a greater range of functions at low cost and can be integrated to provide a more complete contextual analysis, while power supplies can better meet the needs of mobile robots (and may, in the future, be based on novel developments in high density energy sources at low cost for the car industry, e.g. batteries). Moreover, as regards the physical movement of limbs, advances are bringing robots closer to working safely with humans.

EU competency in robotics research is high, with world-leading R&D. The EU industry also possesses a strong technical and commercial competence in the robotics sector in several Member States – notably, France, Germany, Italy and Sweden – and has built up skills for large manufacturing users. These strengths could now be refocused on the emerging robotics markets.

At a commercial level, the EU industry is maturing with ecosystems growing up around systems integration. Value chain analysis highlights some interesting characteristics of the current industry: for instance, the robot itself is less than half of the total cost in many installations. The greater part of the cost is often the systems integration service, programming and auxiliary systems such as interfacing to feeder machines, safety surveillance and emergency controls. This favours the twin strengths of the EU industrial eco-system – systems integration and software production in its various forms – from robotics operating systems and application modules to simulation packages used to build robot-centred production systems.

In consequence, despite economic shocks and a downturn in demand from traditional customers, the outlook for the robotics industry in the EU is still healthy. The state of the EU robotics industry is thus promising in that it has several strengths that could form the basis for transition to a new phase for the industry, which could have effects at a macro-economic level for the region.

Promising areas for Europe

It is in this context that the report examines two particularly promising areas of robotics in further detail, which point to new opportunities for Europe. These are:

- The market for robots for small and medium enterprises (SMEs).
- A new approach to safety and the safety technology developments that could be embedded in future robots.

These two techno-commercial areas were selected for deeper analysis not only because they offer strong market potential but also because the EU's technical and commercial prowess could serve these markets.

SMEs are an opportunity segment for Europe, with its preponderance of small companies. The number of SMEs (defined here as employing 1 to 249 people) in the EU27 is 99.8% of the estimated 20.2 million EU non-financial companies. For the robotics industry, SMEs are a largely untapped market. However, the demands in the SME segment differ in many respects to the mainstream large corporate manufacturer of cars or refrigerators, which use continuous production lines. SMEs require lighter, lower cost robots, plus human interfaces for programming by relatively unskilled staff. These robots must be highly adaptable for short production runs with lower systems integration costs. A major survey conducted in selected EU countries found that some 70% of SMEs using robots and that were planning to further invest in robots, were very interested in robots of this kind. Researchers and robot manufacturers – both established and new - are developing robots to meet this potential demand.

Safety has always been important to the robotics industry. However, if applications are to grow outside traditional mass manufacturing, assuring safety becomes crucial. In traditional industrial settings, safety is assured by separating humans and robots, placing robots in protective work cells. However, with more and more applications envisaged where robots either work in close proximity to, or serve, humans, a completely different approach to safety is needed. The new approach borrows from road vehicle safety by first building a picture of how injuries occur and to what extent. This is leading to the design of new robots which are lighter, softer and more controllable, so that any impacts that do occur are much less damaging than those associated with traditional industrial robots.

The EU robotics industry is aware of the opportunities arising from a new generation of robots, based on safety in the workplace and the ability to work alongside humans. This awareness comes in part through participation in the EU Framework Programmes for Research and Technical Development. The industry is building on early research findings which point to combining safety inherently built into the robot, with models of 'soft' robots for co-working, as being potentially attractive in many market segments, including SMEs. The EU has an early lead here over other regions as important conceptual and more technical research has been undertaken through Framework Programme projects. These include the PHRIENDS project for safer robot technology, and SMErobot, which has examined the SME market opportunities and needs.

The easiest SME market segment to target would be industrial manufacturing, as robots could be used as a 'third hand' in many engineering jobs. However, the food industry, green industries such as solar panels, biotechnology and related sectors could also become major users of co-working robots. Naturally such developments would be of interest to SMEs as well as larger user companies, and there may also be other opportunities – e.g. for safe domestic robots - in adjacent segments. These robots could be first employed in professional service, for instance in hospitals.

Policy support for the robotics sector

As regards policy support for the development of this industry, a different approach is needed to that of the typical EU support for a high-tech industry, which has usually been characterised by important pre-competitive research funding.

Comparing the EU's industrial strategy in robotics with those employed elsewhere in the world is instructive. The Chinese, Korean, and Taiwanese robot industries are all interested in traditional manufacturing robotics and also novel concepts for their mainstream strategy. These countries are all, to a greater or lesser extent, supporting their industries through comprehensive programmes addressing R&D funding, tax incentives, loans, and investment in skills.

To ensure that the EU is in a position to build on its strengths and capitalise on the opportunities now emerging, a more holistic approach is called for, to support the development of a robot 'eco-system', addressing both the demand side and the supply industry. The SME end-user market, on the demand side, needs to be encouraged and educated as does the supply side, which consists of a range of established players and lively new smaller entrants.

Thus the report's key recommendations, intended as input to a robotics industry policy, envisage the stimulation of both supply and demand. This could be done by supporting clusters to act as incubators and enablers with demonstrators and support for the SME end-users, and also providing market opportunities for suppliers. The Swedish robot valley (Robotdalen) is highlighted as a possible model for formation of clusters.

The EU can also learn from other features of industrial policy in other parts of the world. One notable difference in Asia is the emphasis on post-prototype commercialisation, i.e. funding to produce robots or a technology in commercial volumes.

To summarise, the report proposes a strategy for policy support for the EU's robotics sector, with the following main features:

- Policy actions should be aimed at both the demand and supply sides of the domestic market. The bridge between the two should also be understood in order to exploit the role of multiple channels to market.
- Policy actions should address the top layer of added value – design, engineering and software – with a more intense focus on production, including materials and sub-assemblies. This approach accepts that the lower value, basic electro-mechanical and electronic components are likely to be sourced globally and may not be part of the EU value chain. It is a strategy of not only reinforcing strengths but also accepting weaknesses, where a local solution is not viable.
- Effort should be focused on the largest unexploited opportunities, e.g. in food processing, high-tech industries and professional and domestic services.
- Policy should help to build a strong domestic market on the new customer segments with two objectives in mind: first, to equip the emerging user segments (care, SME, etc.) with the means to enhance the EU's general productivity; and, second, to establish robust models and experience before pursuing export markets in the longer term.

If the EU is to make the most of the opportunities now emerging, action is required before others seize the initiative. Key recommendations to develop such a strategy are summarised in the box on the next page.

Key policy recommendations for developing the EU's future robot industry

- **Promote a cluster strategy** which would support the new end-users and innovative new suppliers. The Robotdalen cluster in Sweden could be used as a model and extended across the leading Member States. Financial support should be provided, with a range of measures, from financial support for a business case, to low-interest loans for science parks and 'villages', to formation of interest groups of users.

- **Help innovative entrepreneurs through the 'valley of death'** - i.e. through the phase of industrialisation, post-innovation and the first prototype, i.e. moving from the first working model into commercialised models and then into commercial production.

- E**xpand education in robotics engineering** as a long-term strategy with a pay off only after 5 to 10 years. A combined degree is needed which would embrace mechanical, electrical, electronic and hydraulic engineering, advanced materials, computing hardware and system software and utilities/ cognitive/digital signal processing/application software. A successful course of this kind would require student support; faculty set up; on the job training; vocational apprenticeships; and postgraduate research centres of excellence distributed across EU with specialisations, e.g. visual processing, materials science, muscular mechanics, etc.

- **Raise awareness of the capabilities and benefits of robotics among end-users generally in the EU market** and in specific segments of end-users with promotion and communications to stimulate demand and training support for SMEs. A key part of this would be support for vertical segment demonstrator projects, encouraging new end-users by showing what can be done and at what cost with what risk.

- **Build an EU wide eco-system with local presence in each Member State**, through:
  1. Education of systems integrators (S/Is) with awareness building, then training courses for a long-term build of a support ecosystem for end-users. The aim would be to create a strong S/Is industry of knowledge workers, with high skill content for introducing robots and in vertical applications, also driving high-tech employment and combat the limits on S/Is set by their capability and their commercial risks.
  2. Support for all channels to market.
  3. Encouragement of key technology suppliers (e.g. machine vision) through the cluster strategy.

- **Encourage competition amongst robot suppliers** and technology innovators with support for new entrants, start-ups and high-risk ventures to develop new technologies.

- **Provide financial incentives for R&D and innovation in key areas**, such as mechanicals, materials, and software for human-robot interaction, especially natural language processing and cognition, robot operating systems, signal processing, vision systems, simulation packages, communications, etc.

- **Promote standards in robotics** through standard interfaces for software and hardware applications library with open source software for each segment. This would support the system integration process, encourage competition and lower the costs to end-users in both integration and purchase. The analogue of a robotics industry like the early PC industry, where all suppliers could build to a common platform, is a valuable goal.

- **Support extension of current innovative developments** into a larger professional service segment, and in the long term, care and domestic service segment, through to commercialisation of products.

- **Support the development of a complete legal framework** –to be put in place before the technology– covering robot safety, security and privacy, with protection and/or pooling of IPR to build standard platforms.

1. Introduction

1.1. Context, objectives and approach to assessment

Despite the idea of robots being part of human culture, the robotics industry is still at an early phase of development. A few applications have been well exploited – notably in high-volume manufacturing and most notably in mass production for the car industry. Thus the current stage of development of the robotics industry is essentially analogous to the computer industry when it produced the mainframe, i.e. as a machine for large corporations.

New research directions in robotics technologies promise wide-scale adoption of robots in all aspects of life – from industrial manufacturing to use in professional and domestic service environments. However, applications for small company or personal use are still at the research stage. Though modern science fiction has embedded in our psyche the idea of automated machines with more or less human characteristics, the robotic equivalent of the personal computer, as in the domestic service robot for personal and family use in a household, remains a long-term goal.

Despite this, the question remains of whether robotics technologies are now developing in such a way that they may be disruptive, offering competitive advantage to EU robotics suppliers over rivals in other regions of the world. This, ultimately, was the aim of this study, Competitiveness in Emerging Robot Technologies (CEROBOT), which was carried out for the Institute for Prospective Technological Studies (IPTS) and which is reported here. The study formed part of the COMPLETE (Competitiveness by Leveraging Emerging Technologies Economically) initiative, entrusted by DG Enterprise to IPTS. The objective of COMPLETE was to analyse the prospects of success of the EU ICT industry that could result from new market innovations. The findings will be used to analyse areas of ICT where the EU industry is likely to remain or become more competitive, and to assess the likelihood of commercial success of EU ICT industry innovations, with implications for EU policy. The robotics sector is also of interest because of its potential for a wider disruptive impact on business models and market structures.

1.2. Structure of the report

This report is divided into four main sections. Chapter 2 provides a techno-economic analysis of the robotics sector. Here we briefly explore definitions of robotics, the current state of the art in terms of technologies, current and future applications, the overall market and its potential, the identification of the value chain and its key players. This first step is based on data gathered through desk research and targeted interviews with industry experts in Europe and elsewhere.

Following this initial analysis, Chapters 3 and 4 highlight two aspects of robotics, as examples of that offer particular potential for growth in Europe's robotics industry. Chapter 3 describes the potential for robotics to be much more widely used in SMEs. It describes the SME landscape in the EU, the benefits robots can bring SMEs, the difficulties they face in adopting robots, how these might be overcome and the potential market. The issue of safety in robotics is treated similarly in Chapter 4. Chapter 5 draws together the findings of the study to consider EU competitiveness in robotics, the opportunities and the policy implications. An Interim Report, with a more detailed techno-economic analysis, is available as a separate Annex.[5]

5 This annex is available at: http://is.jrc.ec.europa.eu/pages/ISG/COMPLETE/robotics/index.html

2. General techno-economic analysis of the robotics sector

2.1. Introduction

This chapter describes the techno-economic analysis of the overall robotics sector. It includes sections on the definition of robotics, the state of the art in robotics technologies, applications, the market, the value chain and the disruptive potential of robotics technologies.

2.2. Defining robotics

The term 'robot' has been in use in English since 1923, when the Czech writer Karel Čapek's play R.U.R. was first translated. R.U.R. is an abbreviation of Rossum's Universal Robots, and the word 'robot' comes from the Czech robota, meaning 'servitude, forced labour', from rab, 'slave'.[6]

There is no definition of a robot or robotics that satisfies everyone. Famously, Joseph Engelberger, a pioneer in industrial robotics and the inventor of the Unimate, once remarked, "I can't define a robot, but I know one when I see one". One interviewee in our study remarked that a robot is 'a machine that is not yet here'. In other words it is a concept, a horizon that is forever unattainable. Machines that were described as robots 50 years ago would hardly be thought so today, and technologies developed in robotics are now everywhere, e.g. the sensing technologies in the Nintendo Wii or the iPhone.

Nevertheless, broadly speaking, a robot comprises a computing capability coupled to some form of physical world sensing and manipulation. The International Organization for Standardization defines a robot as "an automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes".[7] This definition contrasts with simple automation, which:

- is for structured environments,
- has no autonomy,
- is capable of no or little variation in tasks and working environment.

Dedicated machine tools or electro-mechanical devices (e.g. a working tool loader for CNC machine tools) are therefore not usually considered to be robots, although Japanese definitions may extend to these machines.

Thus, if we consider all the definitions from a multitude of sources,[8] we conclude that the definition of a robot should include some or all of the following attributes:

- Computing hardware and software, sensors and actuators, usually with more than three degrees of freedom, giving the ability to move in a three- or two-dimensional space with at least three joints.
- Autonomy with some degree of intelligence for decision-making, as set by the necessary degree of human intervention – adaptability for changed circumstances in operating environment. Today, we have limited autonomy and limited tolerance of change. Though automation in unstructured

6 http://capek.misto.cz/english/

7 ISO 8373, www.iso.org/iso.catalogue/ . Manipulating Industrial Robots gives definitions relating to mobility, ability to learn (be taught) etc.

8 See in particular: Computing Community Consortium and Computing Research Association (2009); EUROP (2009). There are also definitions relating to particular robot types, e.g. the International Federation of Robotics (IFR) gives definitions for general and service robots, see www.ifr.org/standardisation and www.ifr.org/service-robots. A wide range of definitions is also available at: http://www.virtuar.com/click/2005/robonexus/index.htm

environments is limited today, in the future it will be possible in increasingly unstructured contexts with high degrees of change, for which decisions are required.

- The capacity to be reconfigured, usually when the robot is not in operational mode –and usually via software–, for a new task or environment.
- The ability to cooperate with humans –this is increasingly important, as is co-operation with other machines (including robots), to tend, service or direct them.

The structure of a classic robot today is a kinematic chain of mechanical parts with a function near to that of a bodily skeleton. It consists of links to actuators (equivalent of muscles) with joints for multiple degrees of freedom of movement. At the end of a 'limb' is a tool, or "end effector", that carries out the robot's task, such as welding.

Physically, robots may be classified by their manipulative degrees of freedom, their mobility and by mechanical structure. Industrial robots and are often classified by their manipulative capabilities, e.g.:

- Articulated robots which have arms with at least three rotary joints.
- SCARA robots (Selective Compliant Articulated/assembly Robot Arm) which have a rigid Z-axis and pliable XY axes, used for assembly in a jointed two-link arm, resembling the human arm.
- Linear or Cartesian or gantry robots which have arms with three prismatic joints with axes that are coincident with a Cartesian coordinate system.
- Cylindrical robots which have axes that form a cylindrical coordinate system.
- Parallel robot-arms which have rotary/ prismatic joints.

The number of axes/degrees of freedom should be understood as the basic feature. Mobile forms of robot can also be classified by form of locomotion:

- Ground transport with some form of caterpillar tracks or wheeled traction.
- Flight: conventional powered flight or ornithopters that fly by flapping their wings, also with thrusters for space.
- Walking with some form of legs –two or more.
- Crawling and climbing with or without legs/arms/hands on the ground, walls, and ceiling.
- Water: surface or submerged, conventional propellers or swimming actions with fins/body.

2.3. The state of the art in robotics

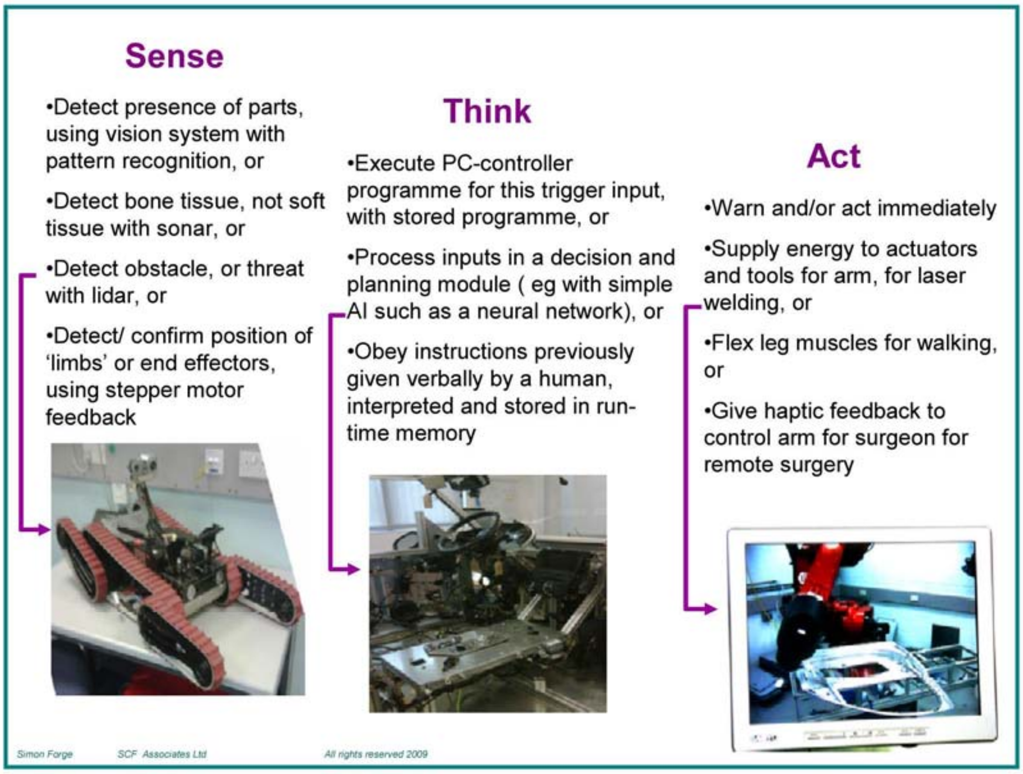
2.3.1. Overview of technologies

Essentially robots carry out three functions –they 'sense', 'think', and 'act'– which form the basis of their autonomy. They 'sense' environmental stimuli and 'think' in terms of preset algorithms for planning and then, on the basis of these algorithms which define the reactions and overall behaviour, 'act'. This three-function process drives actions such as: increasing pneumatic power to orient a picking limb to pick and place a part in a circuit board, or lowering a tray on to a patient's side table. These three functions define the major technologies used in robotics, as shown in Figure 2.1.

From these three basic functions, all robotic technologies can be understood although sometimes they are amalgams of several underlying fields of study. For instance, human interaction must include communication recognition, interpretation and behavioural control.

A brief overview of the key robotics technologies follows.

Figure 2.1: Basic robotic functions and actions with examples



Photos © 2009 SCF Associates Ltd, courtesy Warwick Manufacturing Group, University of Warwick.

Sensor fusion combines sensory data from multiple sources in order to reduce the amount of uncertainty that robots may encounter in understanding the context of their surroundings. This enables a robot to build a more accurate world model, by making it continually context aware in order to successfully operate: it is, for instance, especially useful for helping mobile robots to navigate (Wu, Siegel and Ablay, 2002). Weighting factors can be added to balance for uncertainty. Robot suppliers such as GeckoSystems (Atlanta, USA) offer their own commercial forms of the technology for movement in cluttered environments with orientation and navigation functions.[9] Sensor fusion will be a necessary tool for building a robot capable of acting independently and appropriately in complex situations, in that it is truly perceptive, though this is still a distant goal (Murphy, 2000). European researchers have attempted to bring this goal closer with the Perception-on-Purpose (POP) project and a robot called Popeye.[10]

Human-robot interaction (HRI) - A key attribute of robotics is the ability to communicate and share goals and information with humans, so robots can meaningfully become part of the human environment. Human-robot interaction is based on studying the communications processes between humans and robots. It brings together approaches from human factors, cognitive psychology, human-computer interactions, user interface design, ergonomic and interaction design, education, etc, in order that robots can gain more natural, friendly and useful interactions with humans. For this to be effective at a human level, communications must be multi-modal, integrating speech, gestures or direct digital commands. Some of the application areas, now stimulating research, that will depend on

9 http://www.youtube.com/watch?v=-gM4-pz8dTw&feature=related

10 http://cordis.europa.eu/ictresults/index.cfm?section=news&tpl=article&ID=90953

advanced HRI for close co-working with humans include: home support for care of the elderly, rehabilitation of the frail, hospital care support, education, and emergency first-responder support.

Systems integration - Standard robots sold complete are only one part of the market, and are the lesser part today in value terms. Custom robots are usually required, especially in the manufacturing and process industries. Thus robots in these segments are produced as flexible systems, to be customised and programmed for a target task and work environment. This contrasts with mono-function systems, for instance a vacuum cleaning function or toys, which come with embedded software and require little or no programming, and may even self teach or 'learn' through example. In manufacturing - the commonest of robotics applications to date and where robotics 'grew up', robots are seldom used in isolation – they usually need a customisation phase to fit into their tasks. Here they are equipped with the necessary operational tools, support feeds and safety equipment. Planning and integration in the work environment makes a robot a part of a high speed, precision, flexible production system, able to work reliably round the clock. Systems integrators form their own eco-systems of partners with specialists from across the world to in order to build robot systems that can complete the required tasks.

Cognitive and learning systems - Distinguishing the robot from the digital machine or automated tool rests on a degree of autonomy of decision and a continuous learning ability. Ultimately, this implies that the range of applications may constantly expand. Robots with cognitive capabilities could be flexible in new conditions, as they would be empowered to both learn new tasks and operate and behave in adaptive ways, depending on their changing surroundings. To do this, robots must be able to gather and then interpret the meaning of information from their surroundings, and grasp new tasks. They may then act under the guidance of rules and/or in response to sensory perceptions, to carry out some form of mission planning, in which the strategy for completing a task is mapped out. Robots with even low-level cognitive abilities are relatively complicated compared to their simpler pre-programmed logic counterparts. Beyond having more autonomy in decisions and higher levels of processing of information from sensors, a further and much more complex step for robots is the ability to learn from a situation. This critical area is one of the most promising for the EU industry, which has a chance to lead.

Vision comprehension systems - Today's vision comprehension systems for computers and robotics often use multiple sensors and depend on some form of cognitive processing for scene analysis, although industrial image processing remains quite limited in applications for manufacturing and process control. Such systems, using monocular and stereo vision, often form a key part of the system integration task. They check if dimensions are correct, all features are present, whether a part is left or right handed, etc. Robot vision depends on a range of components, usually comprising: suitable video cameras (also termed vision sensors) with multiple heads; optics, which may require high resolution and depth of field; suitable lighting, often built-in LEDs today; and digital signal processing hardware for real-time image capture and processing. Much of the visual-system cost lies in the vision interpretation software, which may be specialised, by application. As yet, however, most robots cannot infer consequences from natural images, as few have the processing intelligence to draw abstract information from physical observation.

Positioning systems - A key problem for robots is orientation and navigation in the working environment, specifically for collision avoidance. Positioning systems vary enormously in scope and complexity, although the aim is usually to understand the robot's absolute and relative position or that of its key elements (such as an end effector on a moving arm).

This usually requires high precision and often knowledge of the relative position to a target, such as piece of silicon substrate being worked on. For mobile robots, positioning systems enable navigation across a space, by understanding the relative positions of potential physical obstacles. Highly accurate measurement systems may be required, with triangulation or direct distance measurements, using a range of sensors – digital encoders with resistance or capacitive working, LIDAR (Light Detection And Ranging) or laser, infrared, radio phasing beacons or ultrasound systems to position a robot, or its arms and tools. Alternative sensors may use inertial systems for dead reckoning that measure direction and speed of movement from a fixed known point, with equivalents of gyroscope-type sensors such as accelerometers, or simpler odometers, for wheeled or tracked robots. Positioning systems are chosen by application and may be added in the systems integration phase, if required.

Mobility and motion in robots - Many robots need either movement of flexible and extensive arms or end effectors of some kind, from a fixed platform, or complete mobility of the whole robot independent of supply services (especially power). For motion of limbs, robotic arm movements are often highly sophisticated. The lighter ones use DC servo actuators to operate multiple action joints. Jointed limbs with multi-degrees of freedom for manufacturing are well developed – up to 22 degrees of freedom. Arms for industrial applications are designed by weight to lift and torque to apply. In robots with soft, pliant arms, the latest trend is 'variable compliance' which is introduced by antagonistic pneumatic or electromechanical actuation – the balance of two opposing tensioners, as in a human muscle. For larger arms, power can be hydraulic or pneumatic, as in construction equipment. For mobility, various locomotion mechanisms are used – wheels, tracks, and walking limbs (including assisted limbs for the disabled). Wheels and tracks are simpler, yet often just as effective as complex legs. Generally, for safety, all movement of limbs, or of the whole mobile robot, operates with a combination of motion and object detection, requiring a positioning system.

Biomimetics for robot movement - Biomimetic robots are biologically inspired - aping the movement of humans and animals, usually bipeds but also quadrupeds or even insects – e.g. pipeline inspection robots that mimic crawling insects (Na, Shin, Kim, Baek, and Lee, 2009), or wing flapping ornithopters for flying unmanned aerial vehicles (UAVs). The challenge for biomimetic locomotion is to achieve dynamic stability, be it for walking robots – humanoids, such as Sony's SDR-4X humanoid - or for flying bugs or crawling worm-like robots, or robots for climbing. Such robots tend to use analogues of animal or human 'technology' as part of their structure, with muscles and even neurones. Emulation of natural muscles, using biologically-inspired muscle-like actuators is a next step for the humanoid type. Despite over seventy years of hopeful research, complete humanoid robots are still far away. Several threads are being pursued, not only in the development of pure robots but also in cyborg technology for augmenting or wholly replacing human limbs with biomimetic orthotic and prosthetic technology, especially for disabled and injured people (Herr, Whiteley, and Childress, 2003). There are also developments in exoskeletons intended to amplify a wearer's strength, and gloves and wearable devices. Exoskeletons may have a hard exterior like invertebrates.

Gripping/placing/manipulation - Gripping, manipulation and placing are key functions for robots. Robots, which work in the real world, must be able to manipulate objects; pick up, modify, displace, or otherwise have an effect. The 'hands' of a robot are often called end effectors (Monkman, Hesse, Steinmann and Schunk, 2007), while the arm may be referred to as a manipulator. Most robot arms have replaceable end effectors, allowing them to perform a small range of tasks. Some have a fixed manipulator that cannot be replaced, while a few have one very general-purpose manipulator; for example a humanoid hand. One of the most common effectors is the gripper (Monkman, Hesse, Steinmann and Schunk, 2007). In its simplest manifestation, it consists of just two fingers that can open and close to pick up and let go of a range of small objects. Vacuum grippers using suction may be employed by 'pick-and-place' robots, e.g. for electronic components and also for large objects like car windscreens. Although these are simple astrictive[11] devices, they may hold large loads, provided the attaching surface is smooth enough to ensure suction. General-purpose effectors, like fully humanoid hands such as the Shadow Hand, are beginning to appear for advanced robots.[12]

Power supplies - A robot's activity cycle lasts only as long as the power is available. Thus the robot's usefulness depends on its power supply – in terms of rate of consumption and consequently its autonomous duty cycle. For fixed or tethered robots this is far less of a problem than it is for independent mobile robots, where the power supply is part of the weight that the robot must carry. It is, therefore, a limiting factor on performance and ultimately, of acceptance. For instance, the HAL exoskeleton has a 5-hour power supply and without this order of duration), it would be non viable as a lifestyle support tool for the elderly or disabled (Orca, 2009. Forms of energy supply are quite varied. Lead-acid batteries may still be used but are being replaced by rechargeable dry cells. Power supplies in use are highly varied with developments in several new areas: electric – stored or supplied – including dry rechargeable battery, capacitative, radiated/ beamed broadcast power, thermoelectric, inductive coupling (from the floor), piezoelectric and cabled; solar with photovoltaics; pneumatics –either compressed air/ gas or piped; hydraulics– piped or compressed fluids with electrical compressor; chemical –e.g. Hydrogen Peroxide; fuel cells; and miniature internal combustion engines (MICE) with an attached dynamo. More exotic are digestive electrochemical systems, which breakdown biological substances to produce power (i.e. the robot consumes plants,[13] insects, etc.).

Swarms and co-operating robot teams - An emerging field of robotics is based on the concept of simple autonomous robots operating as part of a greater group or swarm, and a new approach to the coordination of multi-robot systems. These swarms consist of large numbers of quite simple robots which operate according to a collective or swarm intelligence based on simple rules, rather than a centralised intelligence. The aim is to produce a desired collective behaviour. This emerges from the interactions between the robots themselves and also between each unit with the environment. Swarming approaches have emerged from the field of artificial intelligence, following studies of insects, ants and other groups in nature where swarm behaviour occurs, such as formation keeping in flocks of birds and schools of fish. Effectively, 'multi-robot organisms' made up of swarms of individual robots can work together to form a single artificial life form. The organisms may be able to share information, and even energy with one another, and to manage their own hardware and software, in order to carry out a common task or work towards a long-term goal.

Nanorobotics - Nanorobotics refer to the still largely hypothetical field of engineering and

11 Astrictive robot grippers are one of the most common methods of picking up, holding or gripping an object, also termed 'prehension'. Such devices form the end-effector at the extremity of a limb. Types of astrictive devices used in robotics and automation generally include: vacuum suction, magneto-adhesion, and electro-adhesion, and also employ other technologies such as piezoelectrics. The most important parameters when considering the implementation of any gripper, including astrictive devices, are retention pressure, energy efficiency, and response time, coupled with the material- and surface geometry-dependent factors (Monkman, G.J., Hesse, Steinmann and Schunk (2007) Robot Grippers, Publ. Wiley –VCH, Germany).

12 Bielefeld University has extended the Shadow hand, see: http://ni.www.techfak.uni-bielefeld.de/robotics/manual_action_representation

13 A concept explored for example in the DARPA-funded Energetically Autonomous Tactical Robot project (EATR), see: http://www.robotictechnologyinc.com/index.php/EATR

Table 2.1: Key robotics technologies, including hardware and software elements[14]

	Likelihood of use in applications	Added value	Complexity (as barrier to entry)
Sensor fusion	High	High	High
Human interaction	High	High	High
System integration	High/mandatory	Med/high	Medium
Cognitive and learning systems	Low	Med/high	High
Vision comprehension systems	High	Med	Med/high
Positioning systems	Med/high	Med	Med
Mobility & motion	Medium	Medium	Medium
Bio-mimetic movement	Low	Med	Med/high
Gripping/placing	Med	Med	Med
Power supplies	Mandatory	Low/med	Low
Swarms and co-operating robot teams	Low	Med	Med
Nanorobotics	Low	High	High

Source: Authors' analysis and interviews with Ken Young, Warwick Manufacturing Group; Geoff Pegman, RU Robots.

design with nanotechnology to build miniature robots (Weir, 2005) for activities at the level of atoms and molecules. Despite the name, size is not well defined, with a range extending from the microscopic scale of a nanometre (10E-9 metres) up to those from 0.1-10 micrometers and some researchers even take it as being as up to a millimetre or so. Such machines at the lower end (also termed nanobots, or nanoids) may be constructed of molecular components on the nanoscale. Suggested designs for the future include the use of sensors, molecular rotors, fins and propellers, to give multiple degrees-of-freedom. Ideally, the sensory capabilities would detect their target regions, obstacles and scene features for the application. This technology promises various futuristic applications, some highly controversial, especially where these robots could be used to assemble further machines, or to travel inside the body to deliver drugs or perform microsurgery. Although artificial nanorobots do not yet exist outside the laboratory, nature's biological 'nanorobotic' systems provide evidence that such systems are at least possible (Requicha, 2003).

Considering all of these technical areas, the question is on which should the EU concentrate to enable its robotics industry to compete globally? Based on desk research and industry interviews, Table 2.1 gives an indication of the likely use of these technologies in future applications, the extent to which the technology adds significant value to future applications, and the complexity involved.

The table thus summarises the most important technology areas for development in robotics. For instance, developments in sensor fusion are highlighted since the need for this in future applications is high and the added value of a robot able to combine sensory data from many sources is also high. It should be noted, however, that the complexity of achieving this is also high.

2.3.2. Future technological development

Building on this assessment, and looking to the future, there are several technologies which the interviewees highlight as requiring significant development for progression of the robotics sector.

- The biggest challenge for robotics research and developers is software. Software must be robust, open (so others

14 Three other component technologies could be added to this list that contribute to the robot eco-system: Sensor technologies; Communications technologies (for sensing, interaction and responses); and Actuator systems and technologies.

can form an eco-system of functional modules on top of the basic platform) and assure autonomous behaviour. It must be self-healing (or autonomic) in case of failure. It has to be flexible and not unique to a particular robot or task. It should be able to integrate and support the most powerful algorithms, as well as new modules for problems we do not even understand today, while driving a range of sensors not yet imagined, with interfacing demands never seen before. Standard robot software platforms (Somby, 2008) are appearing with software development kits (SDKs) to simplify integration and robot development, produced by specialist robotics suppliers (e.g. MobileRobots, Python Robotics' Pyro, Willow Garage) and the mainstream software industry. Certain open source initiatives are becoming important, such as the Robot Operating System (ROS), an initiative based on developments from Stanford University's Artificial Intelligence Lab. Primary development is continuing at Willow Garage,[15] a robotics research incubator in the USA, with some 20 industrial participants including Google, the previous employer of the founders. An open source operating system is highly significant as it enables the introduction of standard software modules connected via standard signal interfaces and programming (via common, open application programming interfaces, APIs) and thus cheaper faster development with plug and play. Bosch of Germany is now participating in the ROS initiative, as well several other EU robotics players. ROS will be integrated with other open source modules, e.g. by the consortium of KU Leuven and others, who developed OROCOS (Open Robot Control Software).[16]

- Power supplies – better power/weight/ volume for energy density has always been a goal for autonomy and is critical for wider use of mobile robots.
- Interfacing with sophisticated sensors in standard ways – connecting up a vision system is not straightforward today. This also applies to interfacing a robot with process equipment in standard ways – as there is a lack of international open standards. Industry standards for the more sophisticated sensors and process tools that will evolve over the next decade will accelerate systems integration and reduce its costs as special adaptors in software and hardware may be avoided, making the integration task easier and cheaper.
- Cognitive processing for safety (e.g., abiding by Asimov's three laws) and far more capability (Asimov, 1940). Total capability is based on a combination of intelligent capacity and cognitive processing for tasks like job learning by demonstration, human interfacing, scene recognition, etc.

2.3.3. Roadmaps for the major capability goals

EUROP (2009), the European Robotics Technology Platform, presented a Strategic Research Agenda for robotics in Europe in July 2009. EUROP's experts forecast that, by around 2020, robots will be working with and for people in more sectors of industry and society, in both the manufacturing industry and the service sector in medicine, logistics, security and space flight and also in the domestic, educational and entertainment branches. Table 2.2 gives an overview of the application scenarios and sectors envisaged.

15 See www.willowgarage.com

16 See www.orocos.org

Table 2.2: Future application scenarios and sectors

Application scenarios / Sectors	Robotic workers	Robotic co-workers	Logistics robots	Robots for surveillance & intervention	Robots for exploration & inspection	Edutainment robots
Industrial	X	X	X			
Professional service	X	X	X	X	X	X
Domestic service		X	X	X		X
Security		X	X	X	X	
Space	X	X	X		X	

To understand robotics' potential, a first analysis is required of when robots are likely to go further in terms of certain essential specific or point innovations. These milestones are largely related to the twelve general technology areas examined in Section 2.3.1, in that they are implementations within one area or a combination of several. Many relate to the interaction between humans and robots, where much progress is needed. Major innovation milestones are assessed, to an initial approximation, in Table 2.3, as indications for a technology roadmap for significant directions for research and development.

2.4. Applications of robotics

2.4.1. Current applications

What we would recognise today as the first industrial robot was the Unimate, introduced in the General Motors automobile assembly line in 1961.[18] Since then a variety of robot applications have been developed and launched, mainly in industrial settings. There are several ways of classifying these applications so, for instance, the International Federation of Robotics (IFR) distinguishes between industrial robots and service robots. Over the past 50 years the majority of robot applications have been in industrial manufacturing, while opportunities are increasingly being seen in professional and domestic service environments.

We have chosen a simple way of classifying applications, in the following categories:

- Medical and care,
- Security,
- Transport,
- Industrial manufacturing,
- Food processing,
- Hazardous environments,
- Agriculture,
- Domestic service,
- Professional service,
- Toys.

Applications in these sub-sectors are summarised briefly below:

Medical and care: The potential for robotics for healthcare could be enormous in terms of health, societal and economic benefits. The prospect of high quality and affordable health provision through increasing use of robotics without compromising quality of care is very attractive, especially in light of the ageing population. Some products are already available, e.g. the da Vinci surgical robot,[19] but we are still in the early stages of development in medical and health care applications. The range of technologies involved and the applications is very diverse. Application areas include (TNO,

17 MIT, Robotic Mobility Group, see http://web.mit.edu/mobility/research/index.html
18 http://www.robothalloffame.org/unimate.html

19 See http://www.intuitivesurgical.com

Table 2.3: Likely timescale for innovation

Innovation	Time scale		
	5 years	**10 years**	**20 years**
Natural language processing for human interaction and specifically as an interface for instruction, to replace programming, with a usefully low error rate (< 0.2%)	Simple phrases and 100 word vocabulary for known speakers in specific situations (responses are strongly typed, low background noise)	Reliable 300 word vocabulary for known speakers with simple sentences, semi-random response, some background noise	Reliable vocabulary for multiple familiar speakers with complex sentences using human style language learning for responses, in high noise environments – may include lip reading
Higher cognitive ability – to use common sense, i.e. human real world logic, e.g. in surgery – or to understand and obey the three laws of robotics	Laboratory, links to CYC and prior knowledge bases	Pilot scale projects	Developed for production in high end machines
Human interaction – real collaboration and co-working with a human in adaptive manner, speech, gestures	Laboratory	Limited use in pilot projects	Developed for limited production for service robots but high cost
Higher emotional intelligence for human interaction – humanoids with empathy, facial expressions, etc	Laboratory	Laboratory	Pilot scale projects in social situations
Expressive robotics – teaching and entertainment Robots	Toys and model kits in mass production	Simple, limited education robots in limited production	Complex teaching robots in full mass production
Humanoids – with full biomimetic functions and a cognitive capability for useful interaction in domestic or industrial environments	Laboratory – collision free movements	Pilot projects and some special market segments for limited roles	Developed for limited production for service robots but too high cost
Human interfacing via thoughts and nerve controls	Laboratory and limited pilot projects especially for disabled	Large pilot real world projects, especially for disabled, frail and elderly	Developed for production
New power supplies – e.g. biological electrochemistry, solar, fuel cells, broadcast/ beamed power	Pilot scale projects	Limited use of biological electrochemistry, solar panels widely used	Full scale production, all types
New sensors – e.g. touch sensitive skin and tactile feedback	Pilot scale projects	Limited use	Full scale production, commonly used
Soft robots which can adapt shape – biological-like, e.g. SQUISHrobot (MIT)[17] – a soft, quiet, shape-changing robot which can climb walls, ceilings	Laboratory	Common use in special applications	Common use in general applications, in mass production
Self-reconfiguring robots that can morph, with hardware, for self-reconfiguration: self-repair, shape morphing, self-replication	Laboratory	Laboratory plus limited self-repair and shape morphing	Laboratory plus limited self-repair and more generally configurable for some special applications

Source: Authors' research.

2008): Smart medical capsules; Robotised surgery; Intelligent prosthetics; Robotised motor coordination analysis and therapy; Robot-assisted mental, cognitive and social therapy; and Robotised patient monitoring systems

Security: Robots have application in safety, security, surveillance, and rescue as well as in military settings. Intelligent rescue systems have been proposed to mitigate disaster damages, for demining areas for humanitarian reasons, and for patrolling facilities for security purposes. But military applications are the biggest segment. Robots are automating military ground systems, permitting protection of soldiers and people in the field, a primary aim being to minimise risks to military personnel and reduce casualties. The US military is investing in increasingly automated systems, e.g. the unmanned aerial vehicle (IAI Pioneer & RQ-1 Predator) and unmanned ground vehicles, such as iRobot's PackBot, or Fisher-Miller's Talon.

Transport: Aside from military transport, applications include automated guided vehicles (AGV), essentially smart fork lift trucks, which are already used extensively for transporting material in manufacturing (e.g. in car manufacturing plants, chemical industry, food and beverages). A fleet of these vehicles can provide a plant with round-the-clock operation, in low lighting but with increased safety and less product damage, while also reducing costs. Robotic transport applications fall under the umbrella of broader, future transport concepts, such as intelligent transport systems, intelligent or smart cars and so on.

Industrial manufacturing: Robots have been used in manufacturing since 1961. Robots are now used in a wide range of industrial applications, including welding, spray painting, assembly, palletizing and materials handling, dispensing operations, laboratory applications, water jet cutting. The earliest applications were in materials handling, spot welding, and spray painting. Robots were initially applied to jobs that were hot, heavy, and hazardous, such as die-casting, forging, and spot welding. These tasks normally take place within separated work cells owing to safety considerations.

Food processing: Applications include picking, packing and palletizing, and robotics in retail has potential to become the next frontier in the food industry. The food industry is still a new market for robots because standardisation is not easy – many products, whether fish fillets or lettuces, vary in quality and size. In the slaughter and meat processing industries, there is growing automation, e.g. carcass splitters hide pullers, although where automation ends and robotics begins is not always clear

Hazardous environments: Robots have many uses in a wide range of hazardous or special environments. These include: clean room, caustic, hot, moist, submerged, high atmospheric, nitrogen or oxygen absent, atmosphere, biological, animal and chemical hazards, nuclear, cold, explosive, shock, noise, no vibration, no light, electrical hazards and radiations, electrical noise, minimal intrusion (laboratory), noise-free, in-vacuo environments, and so on. The goal in most applications is to remove humans from exposure to harm. In cases where the environment would be fatal to humans, robotics offers the opportunity to undertake tasks or processes that previously could not be contemplated.

Agriculture: The agricultural industry[20] has lagged behind other industries in using robots because tasks involved in agriculture are typically not straightforward or completely repetitive under the same conditions. This appears to be changing with renewed interest in the sector. The opportunities for robot-enhanced productivity are significant and robots are appearing on farms in increasing numbers to carry out a variety of tasks, such as: Milking robots; Sheep shearing robots; Crop scouts robot that collect data in the

20 http://robotland.blogspot.com/2009/09/robotics-in-agriculture-reseach-program.html

field; Mechanical weeding and micro spraying robots; Planting, seedbed preparation, spraying, cultivation are all possible with smaller agriculture robots using GPS guidance; Harvesting robots.

Domestic service: These are robots that operate semi- or fully autonomously to perform services useful to the well-being of humans, for instance: Robot butler/companion/ assistants; Vacuuming, floor cleaning; Lawn mowing; Pool cleaning; Window cleaning; Robotized wheelchairs; Personal rehabilitation and other assistance functions. The Husqvarna Automower was the world's first robotic lawn mower, with over 100,000 units sold since 1995. iRobot's Roomba is an autonomous robotic vacuum cleaner that is able to navigate a living space and its obstacles while vacuuming the floor. The Roomba was introduced in 2002 and has sold over 2.5 million units.

Professional service: Service application areas in professional markets with strong growth are defence, rescue and security applications, field robots, logistic systems, inspection robots, medical robots and mobile robot platforms for multiple use, such as: Field robots (agriculture, milking robots, forestry and silviculture, mining systems, space robots); Professional cleaning (floor cleaning, window and wall cleaning, tank, tube and pipe cleaning, hull cleaning); Inspection and maintenance (facilities, plants, tank, tubes, pipes and sewer); Construction and demolition (nuclear demolition and dismantling, robots for building and road construction).

Toys: Robotic toys are produced for entertainment purposes, mainly for children. Robot toys are relatively cheap, mass-produced mechanical devices with limited interactive abilities that may perform simple tasks and tricks on command.[21] Robot toys have grown steadily in popularity since the late 1990s. Significant toy landmarks include the Furby (Tiger Electronics, 1998), Mindstorms (Lego, 1998), AIBO (Sony, 1999) and Robosapien (Wow Wee, 2004). Millions of these toys have been produced.

2.5. The market for robotics

2.5.1. The current market

Revenue figures for the global robotics market are difficult to ascertain. According to the International Federation of Robotics (IFR), the total value of the world industrial robot sales was about $6.2 billion (approx €5 billion)[22] in 2008. These figures do not include the cost of software, peripherals and systems engineering. This might result in the actual robotic systems market value to be about two or three times as large, with the total world market for robot systems in 2008 therefore estimated to be $19 billion (€15.2 b).[23]

The IFR is less clear about the size of the market for service robots – it has given a figure of $11 billion (€8.8 billion) for the total value of professional service robots sold by the end of 2008, i.e. lifetime sales. For the period 2009-2012, it expects the stock of service robots for professional use to increase to 49,000 units, the total value of these robots being estimated at about $10 billion (€8 billion). We might assume from this that the current annual market for professional service robots is worth in the region of $3 billion (€2.4 billion).

In addition, the IFR recently forecast sales of nearly 12 million service robots for personal and domestic use between 2009 and 2012 with an estimated value of $3 billion (€2.4 billion), i.e. suggesting current annual sales of less than $1 billion (€0.8 billion).[24] This would suggest that the current total annual world market for industrial

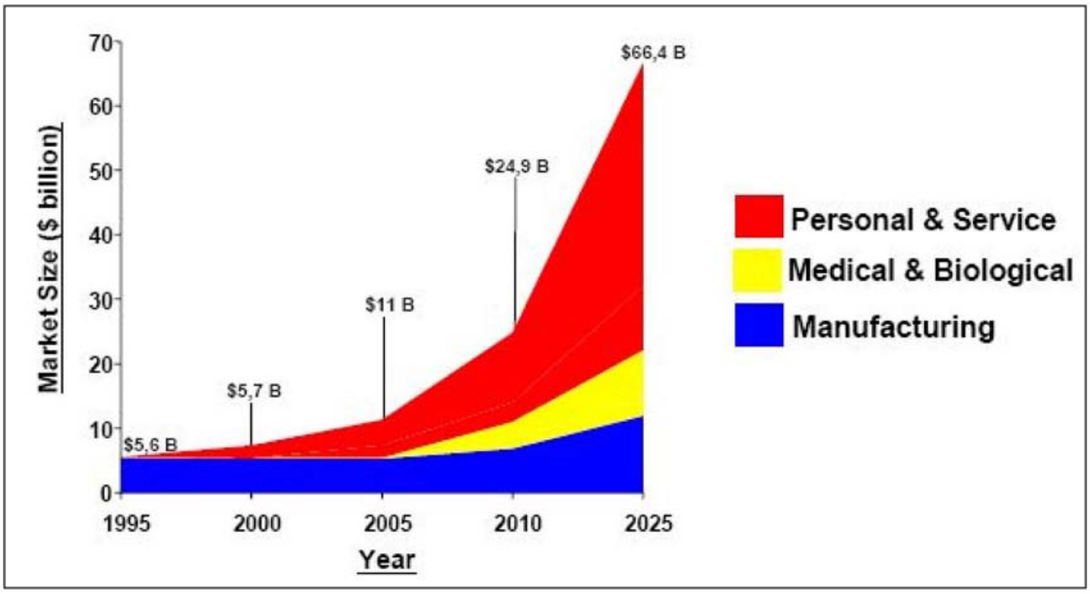
21 http://www.pittsburghlive.com/x/pittsburghtrib/business/s_633005.html

22 At July 2010 exchange rate of approx €1.00 = $1.25.

23 http://www.worldrobotics.org/downloads/PR_Industrial_Robots_30.09.2009_EN(1).pdf

24 http://www.worldrobotics.org/downloads/PR_Service_Robots_30_09_2009_EN.pdf

Figure 2.2: Forecasting size of the global robotics market (2005)



Projection by the Japan Robotics Association, 2005; Source: European Commission, http://www.euractiv.com/en/infosociety/robots-speak-european/article-145529

and service robots is worth about $10 billion (€8 billion).

It is interesting to contrast these figures with forecasts from the Japan Robotics Association in 2005, when they estimated the total global market at that time at about $11 billion (€8.8 billion). At that time roughly half of the market was in manufacturing and half in service and personal robotics, the latter excluding toys (see Figure 2.2).

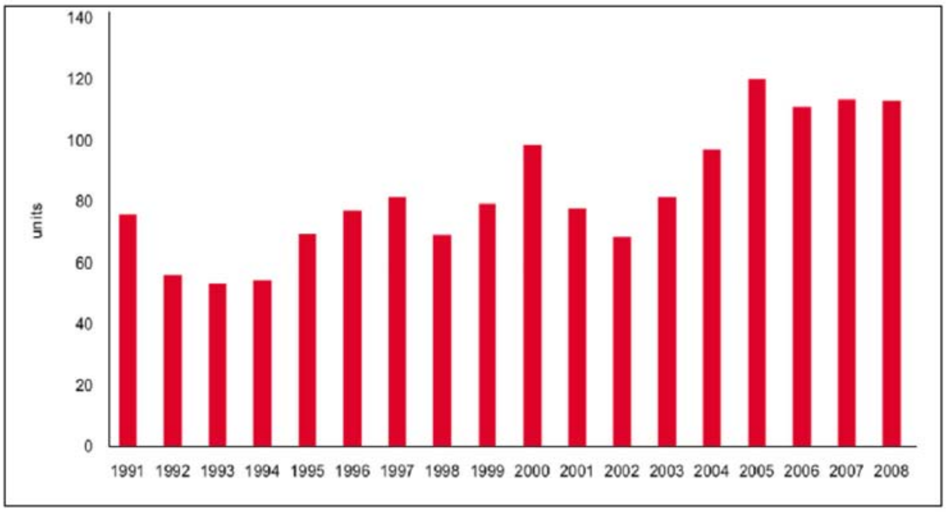
It is apparent that the traditional industrial manufacturing market for robots has been relatively static for over 10 years in terms of sales revenue. Steady growth in sales of industrial robots had been forecast but the value of the market for industrial robots has been stagnant for some time.

If the traditional industrial robot market is saturated, what are the prospects for service robots? It is in the service robot sector that the industry sees the greatest potential for growth. However, as with industrial robots, market forecasts have been over-optimistic and bullish projections for growth in service robots have yet to be realised.

For example, five years ago the Japan Robot Association envisaged tremendous growth in service and personal robotics –by 2010, it was estimated that home or personal robotics excluding toys would be worth in the region of $12 billion (€9.6 billion) (see Figure 2.2). While there has been some development in the personal and service robot market beyond just toys, it has not grown at anything like the rate forecast five years ago. According to ABI Research,[25] the personal robotics market (including toys) was worth about $1.16 billion (€0.92 billion) in 2009, a figure that is in line with our interpretation of IFR estimates. Analysts still expect the market to grow rapidly, but one should be sceptical of ABI's forecast that the market will more than quadruple by 2015, when worldwide shipments will be valued at $5.26 billion (€4.2 billion). Disappointingly, the majority of such robots in 2009 are simply entertainment robots –toys– and single-task robots, such as vacuum cleaners or floor washers.

25 http://www.abiresearch.com/research/1003675-Personal+Robotics+2009

Figure 2.3: Worldwide yearly shipments of industrial robots, 1991-2008 (thousands)

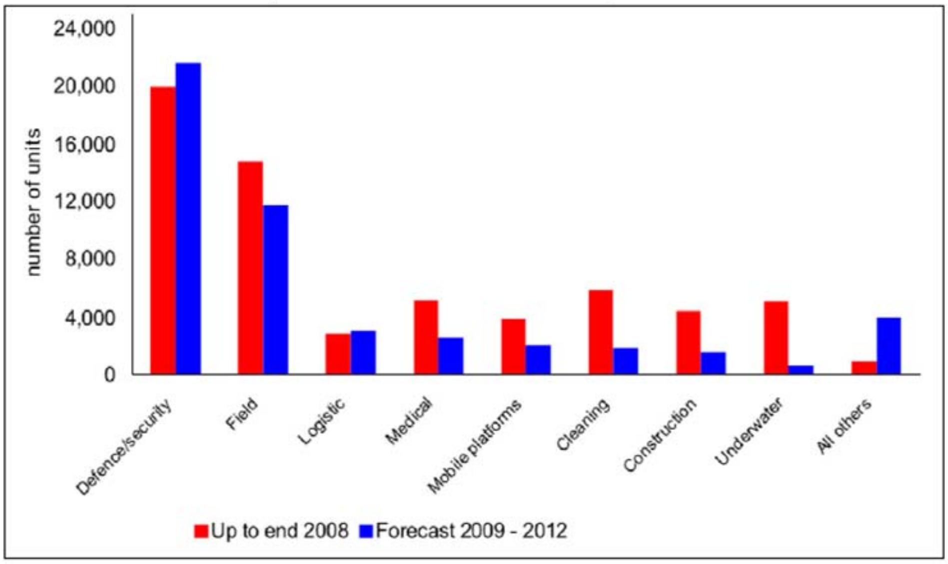


Source: IFR, 2009a.

Estimates of shipments of industrial and service robots from the IFR seem to bear out this analysis. The IFR provides data on annual shipments of industrial and service robots, i.e. the number of units rather than their value, as shown in Figures 2.3 and 2.4. This shows that, between 1991 and 2008, the number of industrial robots shipped annually increased from just under 80,000 to 113, 000, a long-term annual growth rate of about 2.5%.

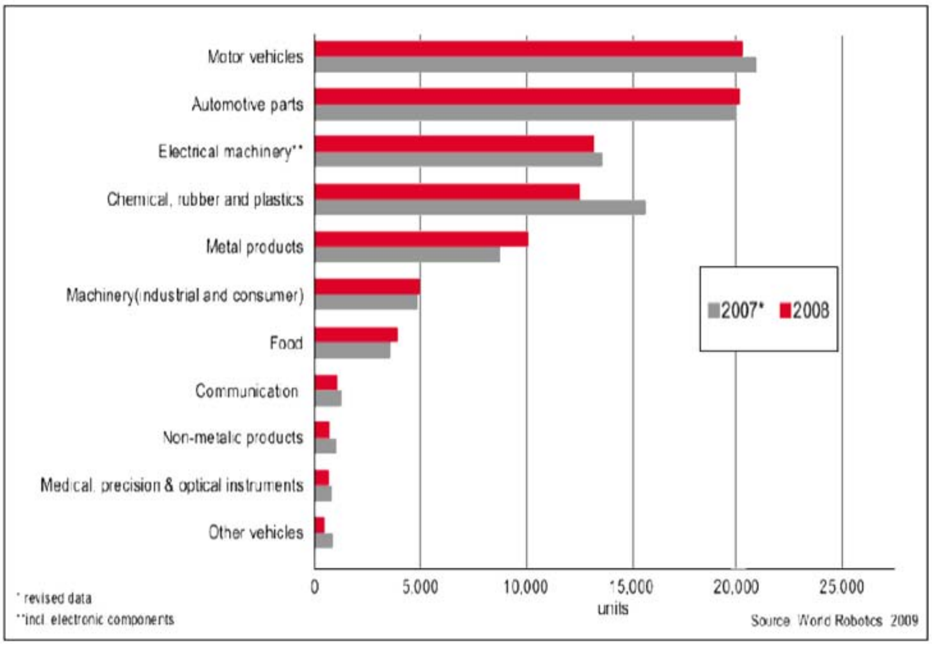
Growth rates for service robots are not available, but the IFR gives a figure of 63,000 as the total number of installed professional service robots, i.e. lifetime unit sales. As Figure 2.4 shows, with about 20,000 units, service robots in defence, rescue and security applications, accounted for more than 30% of the total number of service robots for professional use sold by the end of 2008. This was followed by field robots (mainly milking robots) with 23%,

Figure 2.4: Service robots for professional use: sales up to 2008 and forecast 2009-2012



Source: IFR, 2009b.

Figure 2.5: Annual supply of industrial robots by main industries 2007 – 2008



Source: IFR, 2009a.

cleaning robots with 9%, medical robots and underwater systems with 8%, each. Construction and demolition robots (7%), mobile robot platforms for general use (6%) and logistic systems (5%) came in the next ranges. Only a few unit installations were used for inspection systems and public relations robots in 2008 compared with the previous year.

Although more than one million industrial robots were operating worldwide at the end of 2008, according to the IFR, the sector has been badly affected by the economic crisis since the middle of 2008. In many countries orders and sales were reduced dramatically in the last quarter of 2008. The IFR believes that sales slumped by about 40% in 2009 assuming the global economic recovery has started. If the recovery is slow then it may be some years before the peak production of 2005 can be attained.

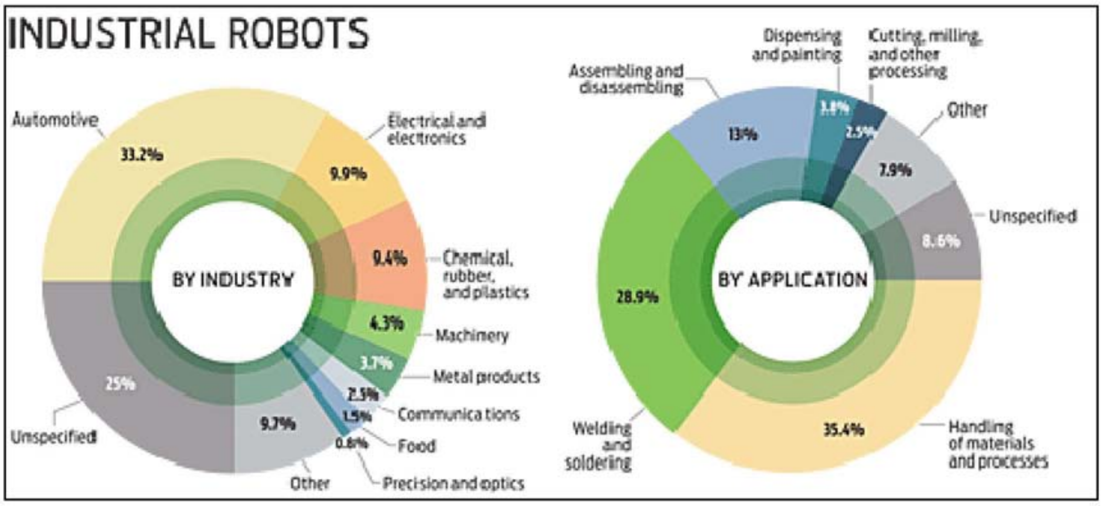
On the back of slow growth in industrial robots over the past few years, the recent slump can largely be explained by the impact of the economic crisis on automobile industry. The automobile industry is the biggest customer for industrial robots and has been through a torrid time since 2008. Figure 2.5 shows that in 2008 the automobile sector held up reasonably well but figures for 2009 will show a dramatic fall.

An indication of the distribution of industrial robots by industrial sector and by application is shown in Figure 2.6.

From a regional perspective, Asia is the largest market, as shown in Figure 2.7, although in 2008 it was expected that the Americas and Europe would be the main regions for growth.

It is interesting to analyse the data by country and by density of robots, i.e. countries with the most robots per manufacturing worker (see Figure 2.8). Unsurprisingly Japan comes out far ahead of any other country when measured this way, but some other interesting facts emerge. For instance, advanced European countries are more densely populated in robots than the USA, and in regional terms, Europe is more densely populated than Asia.

Figure 2.6: Industrial robots by industry sector and application



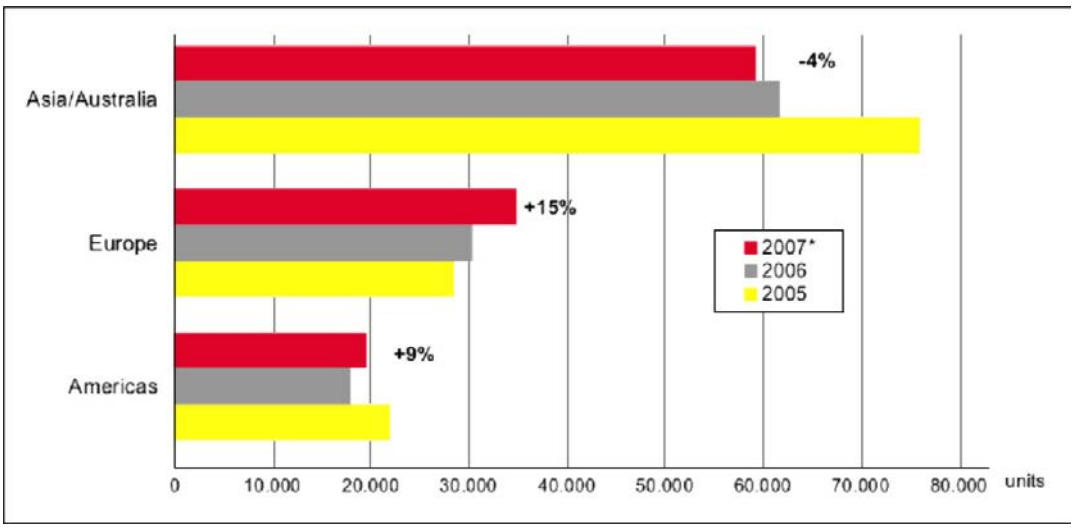
© IEEE; Source: IEEE Spectrum, http://spectrum.ieee.org/robotics/industrial-robots/the-rise-of-the-machines

There are now one million industrial robots around the world, and Japan has 295 for every 10000 manufacturing workers, a robot density almost 10 times the world average and nearly twice that of Singapore (169), South Korea (164), and Germany (163). It should be noted, however, that Japan defines robots very broadly to include automated machinery that might not be included elsewhere.

2.5.2. Market outlook

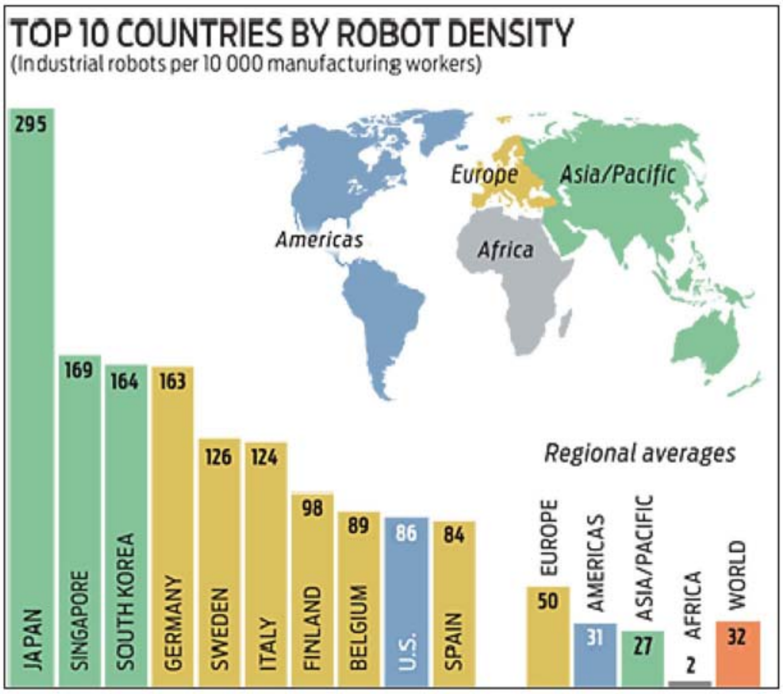
The market picture for robotics has been characterised for decades by overly optimistic forecasts that have not been realised. Our interviews with industry experts and researchers show that individuals in the robotics world are all too aware of the challenges they face in commercialising and marketing robot products. For instance, Box 2.1 is a summary of a leading

Figure 2.7: Annual supply of industrial robots by regions 2005 - 2007



Source: IFR, 2008.

Figure 2.8: Top 10 countries by robot density



© IEEE; Source: IEEE Spectrum, http://spectrum.ieee.org/robotics/industrial-robots/the-rise-of-the-machines
Note: IEEE Spectrum computed the robot density for 67 nations in all, using data from the International Federation of Robotics and the International Labour Organization.

industry player's assessment of some market opportunities. In summary, based on analysis of available market data and interviews with industry experts, a realistic assessment of the robot market and its outlook would indicate the following:

- Slow growth overall in terms of sales revenues for industrial robots is the most likely forecast for the foreseeable future, in line with recovery in the economy.
- The number of industrial robots in the near future will depend to large extent on how the automobile industry recovers from the current economic crisis and how it restructures itself. However, future car production may well be less dependent on robots than in the past as manufacturers seek greener vehicles that may be assembled in different ways.
- Sales of relatively low cost domestic and personal service robots (vacuum cleaners, lawn mowers, toys and entertainment) are likely to recover as the economy comes out of recession, but overall this market is relatively small.
- Professional and service robots are the segments that have the greatest potential for growth. Currently this is dominated by military applications and this is likely to remain the case in the short term. However, there are significant opportunities particularly in health/medical and field robots that offer the best chance for growth in the robot sector.

Box 2.1: An assessment of 'The Business of Robots,' by Colin Angle, CEO, iRobot*

Industrial Cleaning Machines
$80b (€64b) in North America cleaning tile floors but hard to beat labour costs. Huge space needed to be cost effective. iRobot explored and could make 42% savings, but business models substituting human labour are fraught with risk.

Home Cleaning Robots
iRobot's Roomba dominates this market. Price point is anchored to price of vacuum cleaners. There are lots of copies especially in Korea. Marketplace is competitive and margin challenged. Total 2007 domestic vacuum market: $2.4b (€1.9b). Robots have captured 5%.

Home Robots
Popular in Korea. Much scepticism. In some markets, consumers enter with a base model (cars, watches, etc) and over time some upgrade to a premium product. This has not yet been demonstrated in robot vacuums.

Robot Pets
American consumers spend billions on pets. Is there a market for expensive robot replacements? Furby (cheap) sold 40M units, 20M of which were sold for adult use. But expensive Quiro and Aibo were not successful.

Robot Toys
Companies succeed by pushing costs to the factory. If you can give a Chinese factory a design on the back of a napkin, and convince them to build it, you might be profitable. Average cost to develop a new toy is less than $40k (€32k), and 85% only have one-year life.

Above Ground Oil Storage Tank Inspection
iRobot built a product that should have been successful since regulation mandates regular self-inspection. But regulations are not taken seriously. Companies rely on "self insurance". They build in safety berms, and decommission the tank prior to the end of its lifespan. If there is a rupture, they pay the fine.

Military UAV
Unmanned aerial vehicles is a growing market. It has a high price point expectation and over 100 companies involved.

Unmanned Underwater Vehicle (UUV)
Also a high price point expectation, this market is small but growing. A key is the relative lack of obstacles to run into. There are less than 10 companies in this market.

Military Unmanned Ground Vehicle (UGV)
A key market for iRobot. Moderate barriers to entry and a relatively low price point compared to UAV and UUV. Challenges exist in both ruggedness and obstacle avoidance. This market has moderate growth opportunities.

Oil Well Bore Robots
Significant potential in this market. Biggest oil reserves are in deep water and robot boring and exploring robots enable something new. iRobot expects to make a play in this market.

Vending Machines
The most successful robots of all time.

Material Handling
Material handling robots are making a comeback. The offer concrete measures of performance. Very interesting implementations by KIVA systems, Seegrid and Atheon.

Virtual Presence Robots
An emerging market. Builds on the notion of personal video conferencing. Can be applied to both home (jump into your kids robot to talk to them) and business (doctor interviews a patient and checks vitals from remotely).

Animatronics Robots
Disney theme parks have it as a central theme. How about blending animatronics and vending?

Medical Robots
A growing market. Look at the success of Intuitive Surgical and others.

Commercial Exploration and Recovery
Has been lucrative for the few teams that have deployed robots to go after shipwrecks. But definitely not a commercial market.

Audio/video Robot
Do you want your iPod and speakers rolling around after you?

Asteroid Mining Robots
A sci-fi vision. But Google is on the way to the moon.

Conclusions
• Don't be seduced by the cool side of robotics? Who gets paid more, the salesman or the janitor? Value tied to what they produce. (Sex robots?)
• There are interesting things still happening in the manufacturing space
• Medical/Vending/UAV - highest current revenue v margin opportunity
• Is your goal to create a robot that does new things or does things differently?
• Incrementalism leads to slow adoption.
• Is it an industry? Seems like a technology enabler for existing and new industries.

*Source: * Based on a review of keynote at Robobusiness 2008, http://robotcentral.com/2008/04/10/colin-angle-on-the-businesses-of-robotics/*

2.5.3. Major robotics industrial players and clusters

The global robot manufacturing industry is dominated by many Japanese suppliers, such as DENSO, FANUC and Motoman, but Europe and the USA also has some significant players. Europe, for instance, has several major companies specialising in industrial robots, e.g. Kuka (Germany), Comau (Italy), as well as some large conglomerates with a significant presence in the robot market (e.g. ABB (Switzerland), BAE Systems (UK) and Husqvarna (Sweden)). In addition there is a growing number of suppliers serving niche or specialist markets, e.g. Lely' milking robots (the Netherlands).

Revenues for some leading suppliers of robots and robotics technology are shown in Table 2.4. Most larger suppliers are in the industrial manufacturing segment, usually most focused on the auto industry. Note that revenues for 2009 were significantly down on 2008.

Many robotics suppliers, such as BAE Systems of the UK, Denso of Japan and Hyundai of Korea do not give separate figures for robots. For example, although Denso's website (accessed 09 May 2010) gives figures of 42,000 of its robots having been sold worldwide and a further 17,000 being used internally on its own production lines, it sees itself as a high-tech car parts manufacturer, for such items as the power management controller for hybrid cars. So no breakdown of global robotics sales appears to be available. Hyundai of Korea has a major sales operation in the USA and also produces in China, with its robotic products being used in its car plants there, but no global consolidated robotics figure for Korea and its export markets appear to be available. For other suppliers, such as Honda, Toyota and Matsushita of Japan, although robots

Table 2.4: Some examples of robot manufacturers

Supplier	Estimated revenue from robotics sales (€ million) [a]	Employees concerned with robotics	Comments
ABB, Switzerland [b]	731	5000	In 2006 the robotics corporate HQ moved to China. Global sales down 41% on 2008. Robotics is smallest of four main divisions.
Adept, USA [b]	24.1	130	77% of 2009 sales were industrial robotics. Total sales were down 32% on 2008
Aldebaran Robotics, France [c]	1.7 (2008)	80	The first French company dealing with humanoid robotics.
Carl Cloos Schweisstechnik, Germany [c]	114.2 (2007)	600	Pioneers of modern welding technology with two core businesses: arc welding and robot technology.
Comau, Italy [b]	101 (2008)	1000	Robotics represents 9% of Comau's global sales which include welding, power trains, dies, assembly lines, etc
DeLaval International, Sweden [c]	573 (2008)	900	Part of the Tetra Laval Group, supports dairy farming including through robotic milking parlours
Fanuc, Japan [b]	385	5000	Robot Group sales accounted for 29.0% of consolidated net sales in 2009, down 34.7% on 2008.
iRobot, USA [b]	225	500	Grew from battlefield robots for US military. Now also supplies domestic service mono-function simple robots and sophisticated space and professional services robots.
KUKA, Germany [b]	330.5	2000	Robotics is a smaller division than Kuka Systems. Robotics 2009 revenues were down 30.3% on 2008
Lely Industries, the Netherlands [c]	144 (2007)	300	Market leader in automated milking systems.
Motoman, Japan [b]	742	2000	Part of Yaskawa; over 200,000 robots installed worldwide; claims to be number 2 in USA in units delivered.

Notes: [a] 2009 unless stated; [b] estimate based on annual report; [c] Amadeus, Bureau van Dijk, accessed on June 1st 2010.

are a part of their offering, they are a small part. The value of sales seems to be not comparable with their main product lines, which is why perhaps they are not given separately. Again LEGO (privately held) does not break out its robot toy Mindstorms' product revenues although they may be its best selling product line.[26]

Around the world there are several examples of clustering of industrial suppliers, R&D and education institutions in various aspects of robotics. Clusters nationally include:

USA

The most prominent robot clusters in the USA centre on Boston and Pittsburgh (Viscarolasagam, 2009). iRobot is headquartered in Bedford, MA and is at the centre of a cluster of spin-out companies, suppliers and research institutes. Several local companies have spun out from iRobot, including NorthEnd Technologies (Nashua, NH), Cambridge-based Heartland Robotics, and Groton-based Harvest Automation. The cluster includes New England's university community, such as MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL), but also other local universities, including Harvard University, the Franklin W. Olin College of Engineering, Worcester Polytechnic Institute and the University of Massachusetts Lowell, which all have active robotics programs as well. Also,

26 Koerner, 2006. LEGO's first version of Mindstorms sold over a million units by 2006 at an average $200 (€160) with 70% of buyers being adults. The latest versions sell on average for $249 (about €200).

Detroit is starting an automation alley, putting together auto robots and military requirements.

Japan

The Osaka and Nagoya areas are the major clusters of companies involved in robotics technology. Osaka is home to an estimated 1,000 robotics companies and component suppliers as well as leading universities and research institutes.[27] North of Osaka and part of the Knowledge Capital Zone, Robocity Core is being developed as centre in Osaka from which to spur the development of the robotics industry worldwide. Its facilities will include experimental spaces, showrooms, and an open laboratory enabling robotics researchers, technicians and consumers to interact. Osaka City is supporting the creation of businesses and services utilizing robot technology, for instance through its Robot Laboratory facility.[28] The cluster includes the RooBo development platform. This project is a tie-up between a number of companies and researchers.

In Europe there are several nascent robot clusters. Two examples are introduced below:

France

Cap Robotique is the first business cluster in France dedicated to the robotics industry, located in the Ile de France.[29] Led by Aldebaran Robotics and supported by Cap Digital, Cap Robotique is open to companies or laboratories that want to bring thier expertise to the French industry of domestic service robotics. The cluster gathers prestigious R&D institutes like the CEA LIST or CNRS LAAS, but also various innovative start-ups companies, as well as recognized experts in their specialist fields, such as Gostai, Spir.Ops or Voxler. One of its first initiatives is the Romeo project, which aims to design, within 3 years, a general autonomous service robot. Launched in January of 2009, the project is mainly financed by the "Ile de France" French region, the French DGE and Paris city. Aldebaran Robotics led the consortium in charge of its development, composed of 13 world-renowned companies and laboratories.

Sweden

Robotics research and education is performed at technical universities and research labs all over Sweden.[30] Researchers see practical uses for robots in performing socially undesirable, hazardous or even "impossible" tasks such as toxic waste clean-up, underwater and space exploration. Robotics researchers are also interested in robots as a way to understand human (and also not just human) intelligence in its primary function, interacting with the real world. A recent survey conducted by Infonaut identified more than 300 robotics researchers involved in industrial robotics projects.

Robotdalen[31] (Robot Valley) is a Swedish initiative supporting the development of robotics and automation for the industrial, logistics and healthcare sectors. Research and development projects are implemented by small and medium-sized companies, hospitals, global companies like ABB, Volvo, Atlas Copco and ESAB, and at Örebro University and Mälardalen University.

2.6. The robotics value chain

A robot is often part of a larger system, be it industrial or social or for a military task. Design begins with this larger system, e.g., a set of factory cells to process food or a sheltered domestic service situation for elderly care. Here the robot is one component and usually does not suddenly appear fully functional, although there are some situations where this may be so. For example, for consumer products (e.g. toys and floor cleaning) the robot appears independently

27 http://www.jetro.org
28 http://www.robo-labo.jp/english/
29 http://www.caprobotique.com/
30 http://www.infonaut.se/robotics/RoboticsResearch&Education.html
31 http://www.robotdalen.se. See also Box 3.2.

Table 2.5: Use of standard or custom robots by market segment

Application and user industry	Type of required product or service
Toys, consumer items in domestic service, some medical, some military	Standard robots (as a finished standalone product)
Manufacturing and process industries, some medical, military, nuclear	Custom robots for quite specific production environments. Engineering of specialised components, creation of new major components – on demand, e.g. sensors, end-effectors

of its environment although some form of environmental planning and close study of behaviour may have taken place, for functional and liability reasons, by the supplier.

But in many applications, the need for standard robots is rare, as the users always need some form of customisation. Note that this is already approached in the wide range of models and types supplied today by a major player such as Fanuc or ABB. Customisation is carried out in the systems integration phase with special tools and coupling up of power or production supply feeds and outputs. It is possible to classify the needs for customisation and auxiliary specials by application industry, af shown in Table 2.5.

2.6.1. Shape of the robotics industry

The major robotics types of players may be classified broadly as follows:

- Original robot designer and supplier, as a branded product (e.g. ABB in Sweden),
- Systems integration specialist (e.g. M3 or Geku in the UK),
- Engineering of special components (system integrator/ specialist in sensors /actuators /controls/ tools) including value added resellers (VARs) – who are usually specialists in vertical applications and the tools/ ancillary systems required – e.g. laser welding applications,
- Supplier of standard components –sensors, motors, actuators, electronics etc - to robot builders,
- OEM –white label manufacturing for others in bulk volume (e.g. Peak Robotics in the USA),
- Various categories of software suppliers.

2.6.2. Robotics Software

Suppliers to the robotics industry include independent software vendors (ISVs) who sell generic software packages or those specifically for robotics. For instance, Dassault Systèmes sells the CATIA CAD package across many sectors for 3D design. It also sells the DELMIA package which

Table 2.6: Software suppliers to the robotics industry

Software type	Function	Typical source of software
Robot operating system	Manage operation of robot in real time in response to application and perhaps sensor/actuator interrupts	Robot OEM (proprietary) or open source group or ISV for real time operating systems (e.g. Wind River)
Operational application	Programming to enable robot's task	OEM or S/I or VAR
Programming languages, development environments and software tools	Support robot programming, usually as simply as possible. May be quite high level - e.g. just stepping through movements which are recorded by the programming software	OEM (proprietary) or open source group, or ISV, or often a mix, centred on the S/I who may buy an environment to develop the application
Device drivers	Handle actuators and sensors	Robot OEM supplier or supplier of sensor or actuator, or robot tools supplier, or from S/I or VAR
Simulator	Simulation of robot in action	ISV or OEM robot supplier. May be sold as service, not a product.

has simulation capabilities including those for robot cells. Virtual reality simulation may even be used, e.g. for preparing the Mercedes-Benz virtual factory. With virtual environment simulation products, such as the Virtalis SteroWorks VR suite, linked to Dassault Systèmes Product Lifecycle Management package, production of the Airbus A 350 XWB is currently being simulated. The systems simulate every part interfacing and each human and robot movement in the manufacturing process (Davies, 2009). The VR environment is itself based on a robot arm, from Haption, who licences to the arm's force feedback technology from CEA of France. Such packages can also analyse queuing of parts between robots and the buffer stores needed, as has been simulated for a Nissan factory in the UK. For new software creation, Microsoft sells its Robotics Developer Studio (RDS). Table 2.6 presents main software suppliers to the robotics industry.

The complex mix of roles for robotics system integration especially is highlighted in Box 2.2 with an example in aircraft manufacturing.

Thus in industrial robotics, the *robot itself is perhaps less than half of the actual applications cost* –for example for a flexible assembly application (see Figure 2.9).

Despite these variations in robotics technologies and functions, it is possible to view the overall robotics value chain with a generalised model for an approximate industry-wide value structure, as shown in Figure 2.10.

Major differences between the market segments exist due to the auxiliary systems. Some auxiliary systems and their integration demand major investments, often larger than the robot itself (see above box on Airbus Industries example) and may lead to significant variations between value chains both for sectors of application and for individual cases.

Moreover the complete critical path for robotic system creation may require separate value chain 'tributaries' to feed-in the auxiliary systems, e.g. for a specialist chip design for rapid cognitive processing with low electrical consumption, as a vision and scene processor.

Consequently the robot fabrication itself is only part of total value of implementing a robotic system. Systems integration costs and effort to get a useful working robot in a production situation require far more time and effort, especially with the costs of auxiliary systems. Note the strong relationship between the type of application area

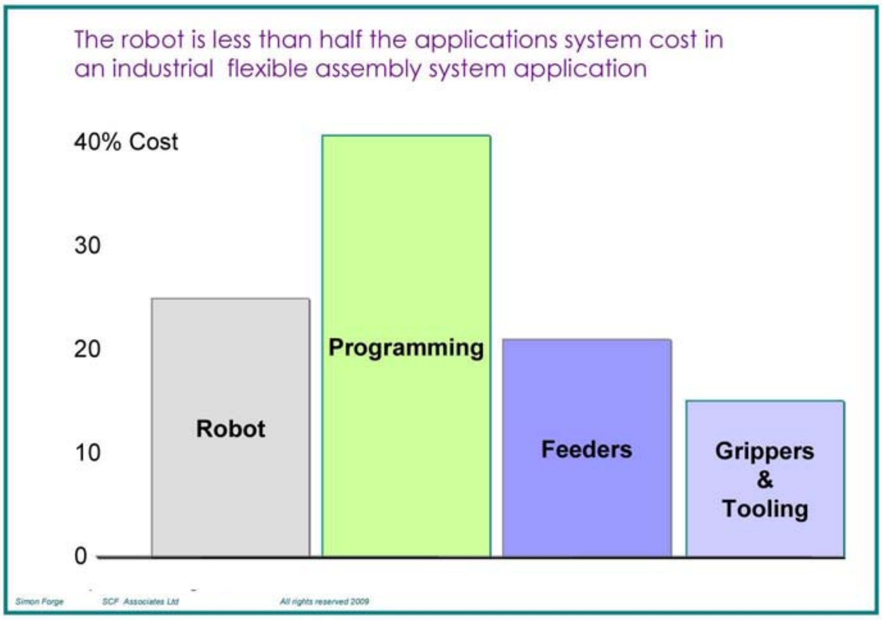
Box 2.2: Example of systems integration for robots in the aircraft industry

One project in Airbus Industries is to accelerate drilling, using KUKA robots, with system integration managed by a specialist integrator, M3, using robot position control software from DELMIA, for some 50 million drilled out spaces per year, all to far higher tolerances than conventional drilling robots can achieve. The target is 0.2mm tolerances, by integrating with a special measuring system from METRIS, with offline programming, to compare actual drill-head position with the CAD system, in order to guide the robot.

The position system uses three CCD cameras for real time co-ordinate positioning with infra-red LEDs as positioning beacons on the jig holding the part (e.g. a wing sub-assembly) and on the part itself. The project requires integration of co-operating robots, with one holding the work piece while the other does the drilling. Thus robot movements need to be synchronised and also must anticipate movement, a function of both the KUKA robot and the DELMIA control software.

Source: Woodruff, 2007.

Figure 2.9: The industrial robot is only one cost item for the total production system



Source: Mauro Onori, KTH, Sweden, 2003, Automatic Assembly Systems/ B.Carlisie, Adept Technologies, USA.

Figure 2.10: A generic model of the value chain for the robot across all applications

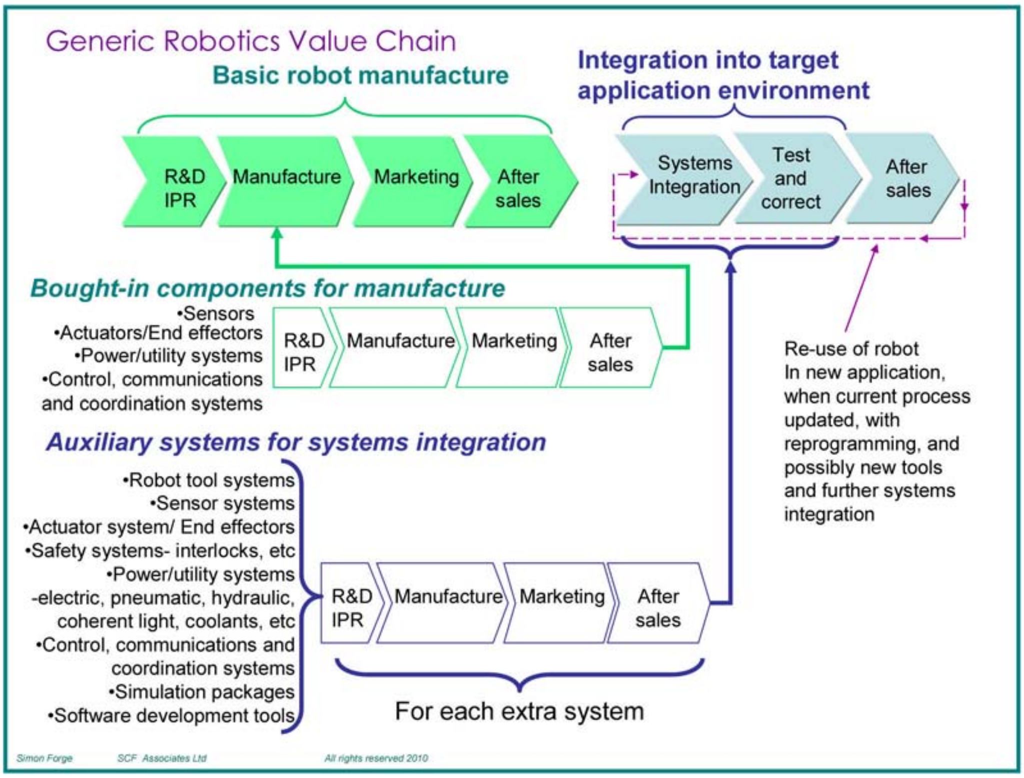
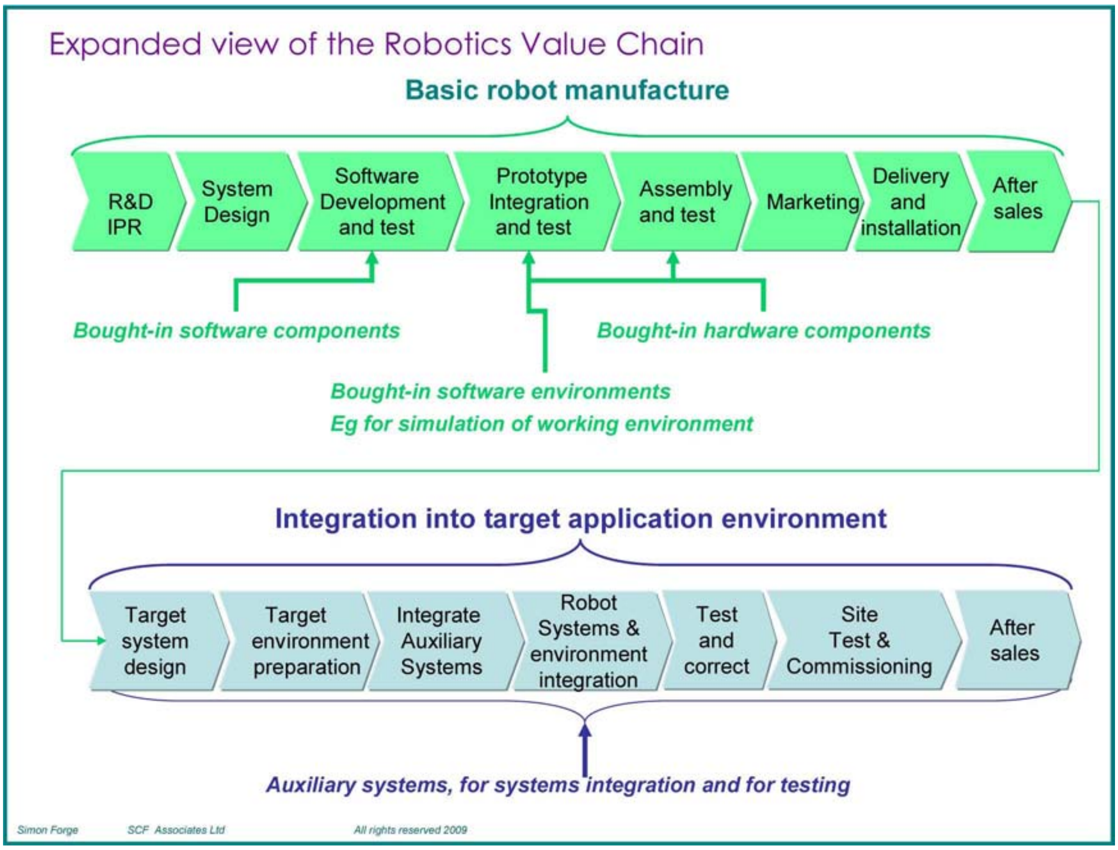


Figure 2.11: Full value chain for building robot and system integration



(e.g. in manufacturing or process industries) and the need for systems integration.

From the above example we may see that the integration process has several stages, as shown below in Figure 2.11, while the basic robot creation itself is more complex than the simplified overview showing the feed-in tributaries.

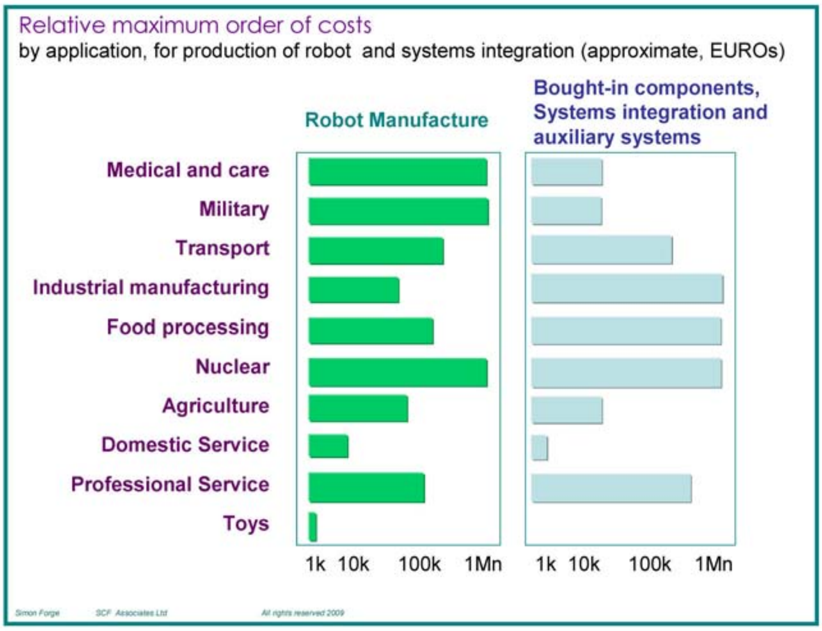
Note that integration includes a phase of preparation of the target environment, which may include many major activities. It can mean construction of a whole building and its interior for robots – for instance strengthened floors, less air conditioning, no illumination perhaps and no stairs. Special design reduces even more the share of the value of the robot in the overall cost. A clean room solely for robots would have different and fewer entrances and exits, with an atmosphere for the machines only. Hazardous working areas would be especially designed for only robot working with recovery mechanisms in case of their failure. A nuclear plant might be built for final decommissioning by robots entirely, with robots already designed for that in the proximity.[32] The expanded value chain is shown in Figure 2.11.

Taking this further, it becomes evident that the basic robot production may only be a minor part of the total solution value. The balance between supply and post-supply integration gives wide differences between applications segments, shown in approximate terms by application type in Figure 2.12.

Thus the net value of the feeder tributaries to the main robotics manufacture and systems integration processes with the systems integration may hold greater value, with specialist additions

32 http://www.engineering.lancs.ac.uk/ci/Files/projects/bakari.html

Figure 2.12: Relative value of the robot when integrated in target environment, by sector



Source: Industry research from multiple resources, e.g. Adept, Da Vinci, plus SCF Associates Ltd estimates from desk research.

as well as the systems integration, far more so than basic components and robots.

However, electromechanical and electronic components are now being driven down in price. Most motors and gearboxes are currently Japanese, but there are also some good European products, especially from Switzerland (e.g. Faulhaber). Volume production of these components should rise if demand for robotics increases. If production volumes of these kinds of items (e.g. specialised servo motors) were to increase such that they become commodity items, then margins would shrink. In such circumstances it is conceivable that production might migrate from Japan and the EU to China and Taiwan.

As applications are often specific in need, integration of many different technologies are necessary. Thus systems integration skills will continue to be of value whenever the need for one-off systems arises. Software is a major component of this and will continue to be so.

A regional analysis identifies the main companies that fit into the different stages of the value chain as shown in Table 2.7. This shows that different types of players tend to be placed in clusters across the world, e.g. white label production is largely in China.

The above table highlights who operates currently at what position in the value chain. Perhaps of greater value is to understand where EU's capabilities lie in the value chain. It is of great interest is to see if the EU can develop from its strengths in industrial robots and systems integration into new areas such as future domestic robots, e.g. for elderly care. At the moment in domestic service robots of a humanoid type, Japan may have gained the lead. However the point has been made that a walking bipedal robot is not always necessary - a simpler and cheaper robot might be made with wheels that does the same job just as well. Various commentators in our industry interviews noted that the Japanese market is more intrigued by robots generally, especially anthropomorphic types, and perhaps has a better educated market, but is not necessarily more advanced technically than other global players, principally the EU and the USA. Following desk research and interviews with industry experts, our assessment of the relative strength of EU companies across the value chain

Table 2.7: Today's key players by position in the value chain

Player type	Europe	Japan	Korea	China/Taiwan	USA
Original robot designer and supplier, as a branded product	ABB (CH), KUKA (D) Comau (I) Qinetiq (UK) Aldebaran (F) Reis Robotics (D) British Aerospace IGM (Au) Staubli (CH)) Lely (ND)	Denso Epson Fanuc Kawasaki Motoman/Yaskawa OTC Daihen Okura Star Seiki Toshiba	Hyundai DSME (Daewoo) Samsung Robostar	Cengdu Great Industrial Siasun Robot Shenzen Silver Star (vac cleaner) Hangzhou Fivestar Hiwin (Taiwan) FarGlory (Taiwan) Apex (Taiwan) Microstar (Taiwan)	Adept iRobot Raytheon McDonnell-Douglas GE Genmark OTC/Miller
Systems integration specialist	M3 R U Robotics Geku	Fanuc Denso	DSME (shipyards) Aitnix	Siasun Robot Triadtech (Taiwan) Acme Manufg.	Buckeye Machine Wolf Robotics Innovation Matrix Peak Robotics
Engineering of special components	R U Robotics (UK) Star Automation	Okura Denso Fanuc	Korea Robot Inc DSME	Siasun Robot CSEMNC (China Shipbuilding)	Applied Robotics Alio Industries Peak Robotics
Supplier of standard components: sensors, motors, batteries, actuators, etc to branded robot manufacturers	Faulhaber (CH) HarmonicDrive AG (D) Pilz GmbH (D) GVH GmbH SSB Duradrive SEM (UK) Parvex Sick (D)	Denso Yaskawa Fanuc Sanyo Tamagawa Sanyo Denki Toshiba	Samsung Korea Robot Inc Jungwoo Metronix Ban Seok Dong Woon	Nanjing Suquiang Numerical Control (brushless AC & DC Servos) Alteks (Taiwan) Topband (Taiwan) Winbond (Taiwan) Sonix (Taiwan) Shayang Ye	Pittman Applied Motion Honeywell Delta Tau GE Advanced Motion Control
OEM – white label manufacturing for others in bulk volume				Many white label suppliers as for consumer electronics (e.g. for iRobot Roomba) Hon Hai (Taiwan) Active Link (Taiwan)	Peak Robotics

Source: Authors' research.

is shown in Table 2.8. The table also indicates the added value or gross profitability associated with each step in the value chain.

The EU is well placed in systems integration and perhaps better placed than Japan in software used for the intelligent element, from programmable logic control (PLC) type control systems up to simple artificial intelligence (AI) systems. Europe is also well placed in advanced sensors especially using optoelectronic systems. If all sensors become simple solid-state devices this could imply that their production moves to China and India. However, labour is a relatively small part of their cost. So they could continue to be produced in Europe, with application of robotics and automation.

Specialised software has the best chance of all components of maintaining higher prices and margins, e.g. in task planning in real time, the robot's processor has milliseconds to produce planning results. Here the EU is well placed. However until recently, the EU has not been strong in batteries – a drawback, as this is a major opportunity for components entry. But this is changing. Batteries for electric cars are to be produced by Tata in Denmark and by Nissan in the UK. Lithium-ion batteries for cars would also be quite compatible with robots' requirements.[33]

33 Interview with Ken Young, Warwick Manufacturing Group, car power demand characteristics for discharge in torque/speed terms are not the same as a robot's but are comparable.

Table 2.8: Assessing the position of EU companies across the value chain

Area	EU position	Added value	Comment
Robotics manufacture for industrial applications	Strong - world-class	Medium	EU at level of Japan, Korea and USA
Robotics manufacture for professional service robots	Strong - world-class	Medium	EU at level of Japan, Korea and USA
Robotics manufacture for domestic service robots	Weak	Low	Some design in Europe (e.g. Karchner) but manufacture largely in Asia. Japan ahead in humanoids.
Electromechanical components	Fairly strong only at the high end for precision servo motors, etc	Low margins except at high end, and all currently descending	Japan is leading producer. China/Taiwan and Korea entering.
Electronic components	Weak, with some exceptions in special processors. Absent in some categories, e.g. passive components	Low margins except for some specialised signal processing and high power processors	Leading producers are China, Korea, Japan, Singapore, Malaysia, and also USA for microcontrollers and microprocessors
Power supplies including batteries, fuel cells and internal combustion engines	Weak	Medium	Japan is leading producer. China/Taiwan and Korea entering.
Electro-optics	Medium/strong	High	EU good at special systems
Sensors	Strong - world-class	Medium	EU R&D effort has produced strong offerings in specialist sensors
Communications and radio positioning	Strong - world-class	Medium	EU is advanced in radio systems and iGPS
Specialised software for manufacture / process control	Strong - world-class	High	A wide range of specialist packages available to integrate
Specialised software for cognition and machine intelligence	Strong - world-class	High	EU has many bespoke systems with basic knowledge and experience
Systems integration	Strong - world-class	High	The EU's strongest area and well-suited to its industry structure

Source: Authors' analysis, based on desk research and interviews with industry experts.

2.7. Distribution in the EU robotics market

There are several different routes to the market for robot manufacturers. The added value in systems integration, add-ons, vertical specialities and ancillary services means there are a number of routes to market, quite apart from the direct sales forces of the major OEM vendors. Over the years a number of channels to market have been built up, which may be just as important as the OEM's direct sales force. The major components of the EU channels map are shown in Figure 2.13 for the non-retail market of business robots (i.e. excluding consumer sales for domestic service types and entertainment such as toys through the standard retail channels).

The various market channel partners are explained in Table 2.9.

2.8. The disruptive potential of robotics technologies

Singular events that may present opportunities for industry opening often centre on a 'point of discontinuity' in a technology. Potentially they can enable entry of new applications, business models and create whole new market segments. For instance, development of a novel type of low-power RISC microprocessor for mobile handsets, contrasting strongly with the types used in PCs, opened up a new global market, enabling new players with new technologies and business models to enter the world microprocessor market.

Figure 2.13: Distribution channels for robots and robotics technologies in the EU

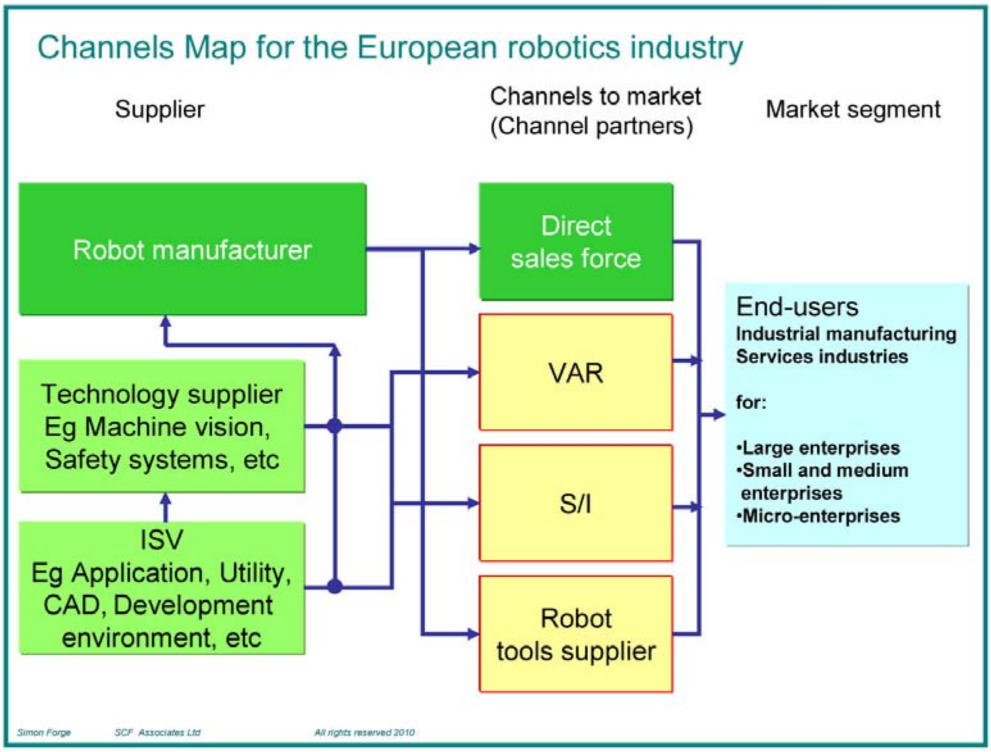


Table 2.9: Channel partner types and definitions

Channel partner	Description
S/I, systems integrator	Integrates (in the customer) all the mechanical systems, robotics hardware, software and special subsystems, e.g. for positioning, and then programs robot for its task, often with simulation beforehand. Acts as major reseller channel for all main robot suppliers. The portfolio of S/Is is a key competitive advantage for a robot supplier as it gives entry to new vertical market segment and is essential to cover all geographic markets. Often, without a capable S/I, it is impossible to enter certain markets.
VAR, Value Added Reseller	Intermediary that buys a robot as part of a total system and resells it in an integrated package to end-users, e.g. welding tool specialist that sells robot with tools, plus extra hardware and software integrated into flexible welding robot. VARs act as a reseller channel for robot suppliers. The portfolio of VARs is a key competitive advantage for a robot supplier as it gives entry to new vertical markets. Often without a VAR it is impossible to enter certain markets.
Robot tools and subsystems supplier	Sells tools and subsystems to end-users, as well as to robot manufacturers or system integrators or VARs. The tools supplier may have moved into robots from selling tools on a standalone basis, e.g. for welding, or hazardous cleaning, when the original tools would have been manipulated manually. SMEs are often customers for manual tools which become automated through the tools supplier, so that robots then enter the user company. Again, having a comprehensive portfolio of complementary tools suppliers is massive advantage to a robot OEM.
Direct sales force	OEM's own sales force, selling robots directly to customers. Always used for large customers, in order to cut out intermediaries and their margins. Thus sales force personnel ('sales engineers') tend to be specialised vertical sector experts, i.e. sector knowledge/experience (and reputation, contacts, empathy, etc) is high, e.g. in cars, aerospace, electronics assembly, food processing, pharmaceuticals, etc. Tend to have complete manufacturing process knowledge for a specific industry and know all the appropriate partners for a specific project.

The question is whether any signals of disruption in scale of use and directions in robotics technology can be detected.

2.8.1. Social, economic and other factors

In addition to technological innovation, there are several other factors that are likely to influence take up and increased use of robots. These include:

Social changes: the pressures of an ageing population bring new demands at a mass-market level, perhaps changing the future direction of the whole robotics market away from its industrial manufacturing roots towards new domestic service applications. Today, this is inhibited by price. Researchers at the Fraunhofer Institute, for instance, believe that a personal domestic robot with more than basic functionality would need to be available to consumers at a price similar to a good quality car (about €40-50k) to enable significant take up.[34] However, a price point of below €30k (except for early adopters, perhaps €50k) is possibly the limit that can be afforded for widespread take-up. Other potentially significant robotics technologies such as the exoskeletons for the mobility of the aged, now in early forms such as the Japanese HAL exoskeleton robot, have a market price somewhat higher than this, in excess of €50k. HAL only rents currently, and it is likely that new business models will be necessary for widespread take up (e.g. with national health services playing a role).

Widening professional markets to SMEs: technical advances that give lowered costs open new market segments – specifically for SMEs, the largest segment of company types (over 95% in Europe) and who dominate some key European segments, such as food, agriculture and light engineering. Here, a price point is needed, with systems integration, that may be below €100k before SMEs will take up robotics on a large scale.

Environmental impacts: robots have a part to play in more efficient and cleaner processes as well as in the environmental industries. EU leads in robotic solar panel fabrication (Burnstein, 2009).

Globalisation: early markets were in the OECD countries, with China recently installing robots especially as car manufacture took off and manufacturers such as Hyundai installed their welding and assembly robots there. Today robotics products are being sold, and made, in parts of Latin America and Asia, such as India.

2.8.2. The technological disruptive pressures are incremental

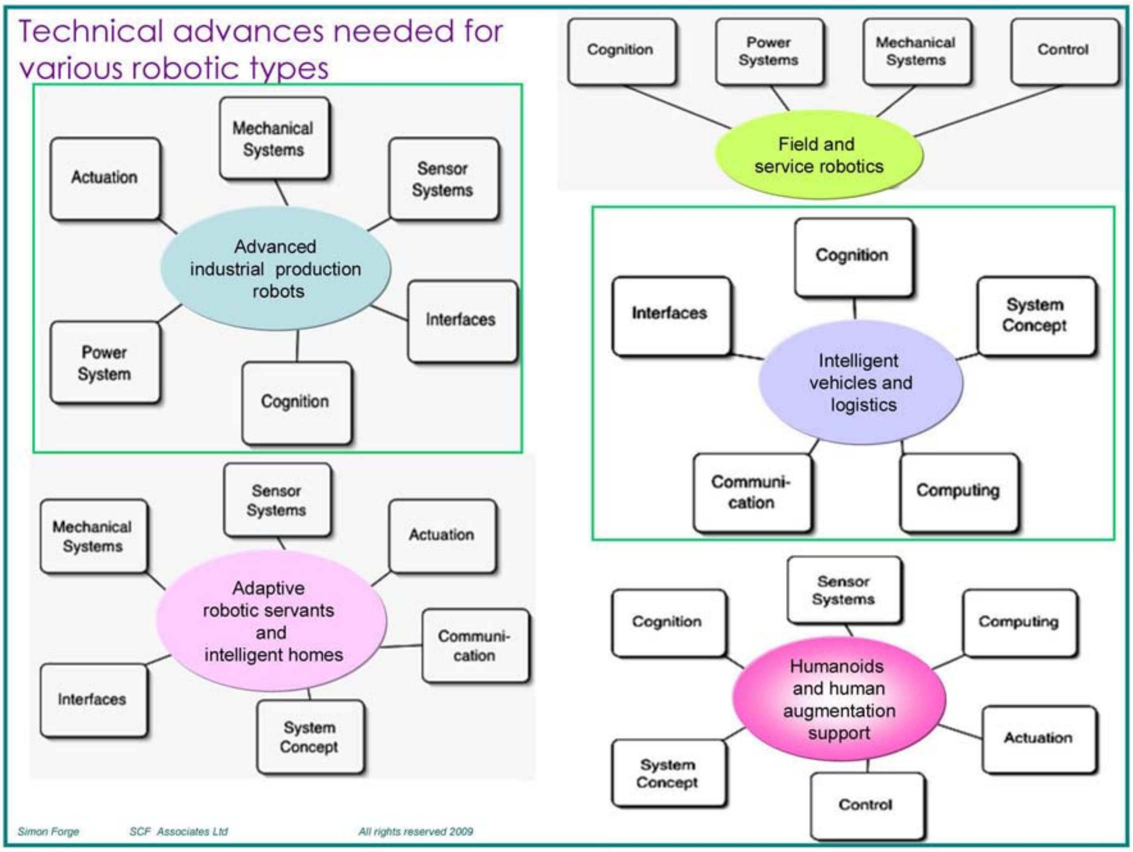
The evidence for a major technological discontinuity is absent. Instead we may observe

Table 2.10: Functional advances needed and technology drivers

Key functional advances to build critical mass of change	Technology Drivers
Autonomy for decision taking with human safety	Sensor fusion
Collaboration with humans, other robots and machines	Human interaction
Navigation safely	System integration
Object detection	Cognitive and learning systems
Person detection	Vision comprehension systems
Collision free manipulation	Positioning systems
Scaling of intelligent machines, especially miniature	Mobility and motion systems
Energy consumption for mobile robotics	Bio-mimetic movement
	Gripping/placing
	Power supplies
	Swarms
	Nanorobotics

34 Interview with Birgit Graf, Fraunhofer Institute.

Figure 2.14: The technical advances required, analysed by certain application segments



Source: EURON Research Roadmaps, European Robotics. Research Network, 23 April 2004.

a gradual build-up of many relatively small and diverse advances. In total, the disruptive pressures appear to be incremental, not cataclysmic – and thus not a discontinuity. However, the combination of advances in technologies should gradually make robots progressively more attractive in terms of utility against cost, steadily growing the market to generally. The functional advances and their technology drivers are shown in Table 2.10.

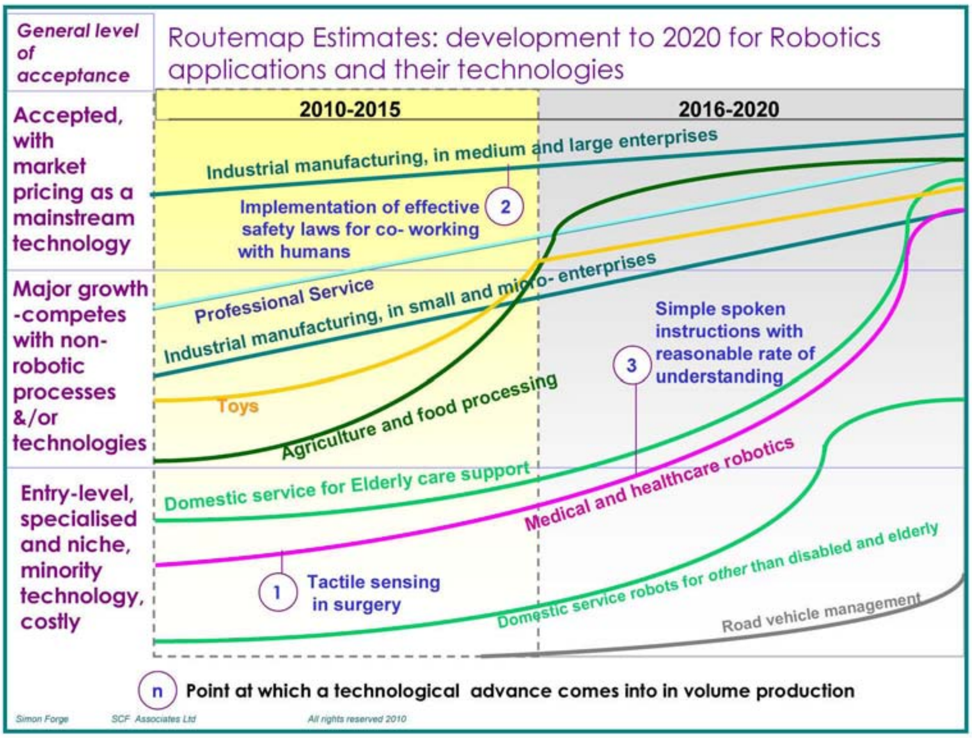
The key technical impacts required for this expansion can be analysed further by market segment, as shown in Figure 2.14.

Collectively these technical advances may achieve a critical threshold of new functionality against cost that could drive world markets. But now to answer the second question - when is this likely to happen? The various likely directions for developments, set out as roadmaps, can be analysed from the literature to provide estimates for the major segments, as shown in Figure 2.15.

Examining each segment, there are quite different paths of development. The rationale behind each estimated path, based on analysis of desk research and interviews with industry experts, is as follows:

- In industrial manufacturing, in large enterprises, robot use is already mainstream. However, the possibility exists for much wider implementation in many SMEs, although this depends on affordability and simplicity. Significantly lower pricing and the need to educate the market mean that it is likely to be more than five years before large numbers of SMEs understand the utility and adopt robotic solutions.
- For the professional services segment, such as pipeline robots or undersea

Figure 2.15: Roadmap of progress and market entry by segment



Source: Authors' analysis.

cable inspection, applications are already growing and are likely to be mainstream by 2015.

- Toys and entertainment are already a small but growing market and will be embedded as part of soft toys in the future, expected to become a major toy segment by 2015.
- Agriculture and food processing is a new 'industrial' segment that requires different handling properties and recognition sensing for organic products, which should be well refined by 2015, when it becomes as mainstream as industrial manufacturing in specific situations, e.g. ploughing on large acreages, or in milking or on-farm cheese-making as well as factory production of foodstuffs.
- Robots for elderly care, as a domestic service category, will take longer to take off for reasons of cost/functionality and acceptance by ordinary people (especially outside Japan). Such robots will only become market-priced for major growth well after 2015. If they can provide good functionality and provide value for money, simple care robots could grow rapidly to be a mainstream product category by 2020, especially if the technology for receiving spoken instructions can be developed. In contrast, more complex domestic service robots for ordinary people who are not elderly, frail or disabled may only grow after 2020 when price and performance gives real advantage over human activities for domestic chores. For most households, even in OECD countries, this is likely to remain a restricted market for the foreseeable future, not becoming mainstream until later in the century.
- For medical robots, the barriers of liability as well as cost and time to educate the medical profession imply a delay in entering the main growth period (the da Vinci surgery robot took ten years to be marketed owing to liability issues). However, once accepted, main growth

should be fast if cost/benefit analysis shows major gains, so that mainstream use may come before 2020, unless the cost/liability/education issues are not resolved.

- For reasons of safety, acceptance and liability, robot road vehicles in a total transport system, may not be generally taken up until after 2020 as a mainstream technology.

Of key interest is the appearance of new entrants to the robotics market and their origins. Players who may compete with EU suppliers may come from adjacent sectors to robotics, in consumer goods and electronics. For instance, Nintendo using the engineering in the Wii games player, with its robust and low cost accelerometers, could be a contender in robots. All that Nintendo would have to add are actuators – and this is a fairly straightforward step. Apple with its excellent user interfaces (UIs), cameras with multimedia applications could also be a contender. It also has strengths in software for web applications and operating systems, plus competences in product engineering and global supply chain management. As the UI is critical for the next stage of robot development, Apple is positioned more strongly than might otherwise be apparent. Obviously Microsoft (Robotics Studio software development platform, X-Box experience) is also a potential entrant. Players such as Sony, Philips and Siemens also have the capabilities for entry.

2.8.3. Selection of two areas for further study

Following this general techno-economic analysis of the overall robot sector, this report now considers some aspects of the robotics sector in greater detail. Several topics[35] that emerged in the initial techno-economic analysis were considered before two areas were selected. The candidates considered are shown in Table 2.11 and are rated according to two selection criteria:

- First, the potential size of the market, and
- Second, the capability within the EU to capitalise on the opportunity.

Examination of the market opportunity requires answering a key question: does the opportunity have the potential to become a sizeable market, i.e. does it satisfy an unmet need? As shown earlier, the robot industry has been characterised by ‘technology push’ over the past few decades and has been particularly prone to over-optimistic forecasts of market demand. In future, it is essential for the EU’s robotics industry to be guided by the market and demand for robot applications.

The second aspect – does the EU have the potential capability to fill that demand? – is also crucial if the EU robotics industry is to maintain and improve its competitiveness. This requires assessment of several factors including: the fit with the EU’s industrial structure; the capability of EU firms with regard to various key technologies; the quality and availability of supporting R&D through universities and research institutes; and the availability of the necessary and suitable skills. Examining these factors will enable an assessment to be made of whether an appropriate robotic industrial eco-system is available or is likely to be built in Europe. In turn, this will allow assessment of whether the EU possesses a global level of competence in this area and whether it might even have a competitive edge over other regions.

The assessment of potential and capability of these candidates were discussed in a selection workshop before two areas were chosen for further analysis. These were:

- safety in robotics, and
- robotics for small and medium-sized enterprises (SMEs).

35 Other candidates considered were: medical/health robotics; sensors for robotics; robotics for food processing and agriculture; large-scale industrial manufacturing; robotics for the environmental industries.

Table 2.11: Assessing candidates for further analysis

Robotics topic	Potential size of market	Capability within EU to exploit
Medical and health care robotics	xx	xx
Safety in robotics	xxx	xxx
Robotics in food processing and agriculture	xx	xx
Robots in large-scale industrial manufacturing	xx	xx
Robotics for SMEs	xxx	xxx
Sensor technologies	xx	xx
Robotics for the environmental industries	xx	xx

Against these criteria, the two areas chosen stand out. As far as robotics for SMEs is concerned, several factors are noteworthy:

- The take up of robotics by SMEs lags far behind take up in large companies.
- The EU's industrial landscape is characterised by many SMEs, many of whom could benefit from robotics with the right formula of functionality, price and ease of use.
- Increasing SME productivity is key to enabling EU competitiveness, creating new products and jobs across the EU.
- EU competence in robotics for large corporations is world class and offers a platform for adaptation for SMEs.

With regard to safety for robotics:

- The inability to ensure safety is a significant barrier to more widespread take up and use of robots. Overcoming this obstacle will drive the whole robotics industry and could give the EU's robotics industry a global lead.
- New, safe robots will facilitate applications in co-working, which is potentially a large market.
- The EU already has competence in key aspects with skills at a worldwide level.
- Safety drives other technical areas with high-added value and intellectual capital.

These topics are now examined in the following two chapters.

3. The opportunity for robotics in SMEs

3.1. Introduction

This chapter deals with a segment of industry –the small and medium enterprise (SME)– which so far has neither adopted robotics widely nor received real encouragement to do so.

Robotics technology has generally been developed for capital-intensive, large-volume industrial manufacturing. The result is costly and complex systems, usually mono-function, which often cannot be used in the context of an SME. The volume scale is often a key part of the economic justification for robot use, usually for rapid movement with high precision in repetitive working. SMEs are sometimes caught in a trap: they must either opt for current and inappropriate solutions that do not meet their needs for small runs and low costs, or else compete on the basis of lower wages.

SMEs are one example of how, why and where robots may be used in new segments to form the next phase of the robotics market's development. Thus this chapter explores how robotics could be taken up much more widely in the SME user market. First the significance of SMEs is examined in economic terms in the EU, their attitudes and barriers to take-up and their potential in market terms. Where and how robots could fit into the SME end-user value chain is then explored, with an SME needs analysis. Many SME robots would be used in sectors outside the industrial sector and consideration of these sectors follows. The position of the EU robotics suppliers to respond is then considered, with the catalysts necessary to trigger take-off for the SME market.

3.2. SMEs in the EU and their use of robotics

3.2.1. SMEs are highly significant to the EU economy

SMEs are a major element of the European Union's industrial landscape and a potentially enormous growth area for use of robotics. SMEs in the Eurostat statistics database include micro-enterprises employees and small and medium firms, i.e. companies with 1 to 249 employees. The non-financial sectors of SMEs could be considered as the largest future potential consumers of robotics. Major SME sectoral divisions are in industrial manufacturing, construction and services of all kinds which are non-financial. Of the minority of SMEs that do use robots, industrial manufacturing SMEs are the largest users of robotics today, but the industrial sector is well under half the size of the SME services sector in total value added and employment. However, per enterprise, manufacturing SMEs add twice the value of the average service firm (see Table 3.1)

Table 3.1: Comparison of SMEs: services, construction and manufacturing EU27, 2005

SMEs	Millions of SMEs	% of total SMEs	Millions employed	Value added (€ billion)
Manufacturing (NACE C-E)	2.35	12	21.1	806
Construction (NACE F)	2.79	14	11.9	386
Services, Non-financial (NACE G-I & K)	14.46	74	51.9	1897
Total Non-financial (NACE C-I & K)	19.60	100	85	3090

Source: Schmiemann, 2008.

These figures reveal the true worth of the SME sector. It is the engine of growth in the EU and also of employment, added value and new jobs, as summarised in the Box 3.1.

The gap in productivity between SMEs and large enterprises is quite evident but is static, as shown in Figure 3.1.

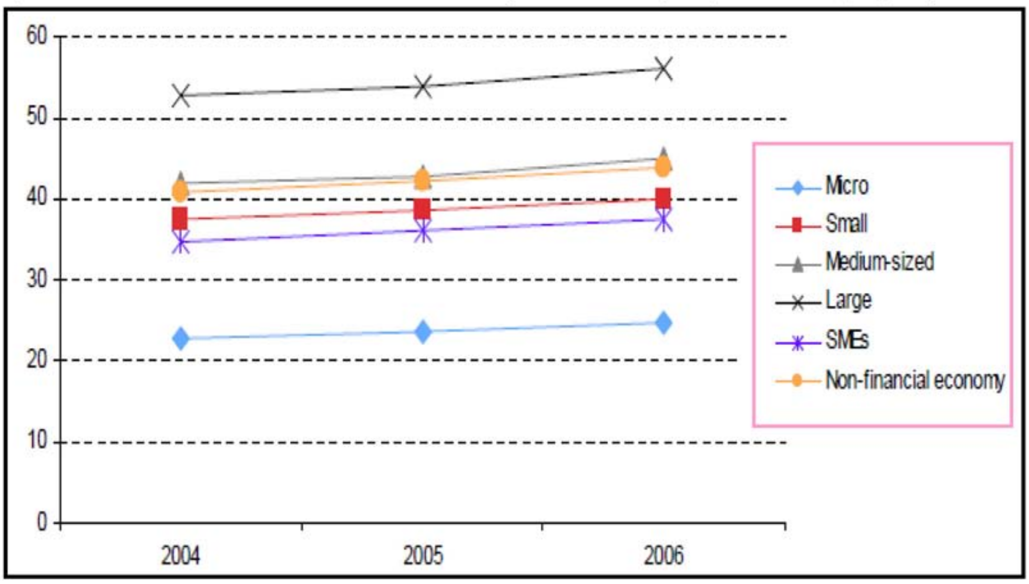
This productivity gap highlights that the EU economy's industrial backbone, micro-

Box 3.1: SMEs dominate the EU non-financial industrial landscape

- The number of SMEs in the EU27 including micro enterprises is 99.8% of the estimated 20.2 million EU non-financial companies when counted as 1 to 249 persons employed per SME to include micro-enterprises.
- Micro-enterprises (9 persons or less) make up 91.8 % of all companies in the non-financial sectors while medium-sized companies are 1.1% and small are 6.9%, large being some 0.2%. Thus the number of micro-enterprises in the EU is around 18.5 million. The standard size of SMEs is now taken as 10-249 employees with small enterprises as 10-49 employees, with medium as 50-249 and micro-enterprises as being below small enterprises.
- Employment and economic power in EU27: SMEs employ 67% of the employees in non-financial business and generate 58% of total added value.
- Job creation power –SMEs were the key drivers of EU employment growth over last period measured by Eurostat, 2004– 2006. Large enterprises tend to shed staff (Peacock, 2010) while new employment is largely driven by SMEs who increased employed numbers by 5% over 2004-2006 while large enterprises in total increased their employment by 3%. Medium size enterprises increased their employment fastest compared to small and micro-enterprises over this period.
- Efficiency as labour productivity in the EU increases with size of enterprise –on average large companies were 50% more productive than SMEs (Eurostat)

Source: Eurostat's portal on SMEs: http://epp.eurostat.ec.europa.eu/portal/page/portal/european_business/special_sbs_topics/small_medium_sized_enterprises_SMEs

Figure 3.1: Apparent labour productivity of enterprises in the non-financial business economy, by enterprise size class in the EU, 2004 – 2006 (EUR 1,000 per person employed)



Source: Schmiemann, 2009.

enterprises, have less than half the productivity of large enterprises. The small and medium enterprises (some 8% of all enterprises) at best lag 30% behind. In industrial manufacturing, a part of the lead of the large enterprise is the productivity owing to robotics. Thus, robotics could offer an advantage to the European economy as a whole, via an increase in productivity, through widespread adoption of robots by SMEs. However the short-term opportunity in the SME segment is in manufacturing of various kinds. The service sector is less likely to use robots, except in specific activities such as logistics or medical care.

3.2.2. Benefits of robots to SMEs

By using robots, productivity gains can be manifested in diverse ways to give a competitive edge:

- Extending the range and complexity of tasks that the SME can perform cost effectively and so extending the competitive scope of the firm.
- Leveraging the strength of robots – especially in goods handling and logistics, manipulation of heavy production parts, etc – to provide greater capability.
- Leveraging robot productivity to perform some tasks faster (especially repetitive types).
- Leveraging robot productivity as a third hand, as a helper having some limited capability for co-operation, if possible in a closely shared workspace with the human workforce.
- Enabling the SME to cope with rapid changes in demand – higher or lower production.
- Coping with hazardous environments, and/or long-term health risks, e.g. chemical sprays.

An important EU-funded FP-6 project, SMErobot,[36] has explored the SME market for industrial robots in a variety of manufacturing applications.

3.2.3. SME sectors using today's generation of robots

From our interviews and scanning industry sources, the major robot manufacturers in the EU now recognise the SMEs as a potential growth segment. In terms of vertical segments, the fastest growing SMEs are in food and beverages and new manufacturing industries for high technologies such as solar panel assembly. What this suggests is that suppliers of robotic products and services for SMEs will need to develop deep sector knowledge. This is especially crucial in the food processing sector because, as one robot supplier noted:

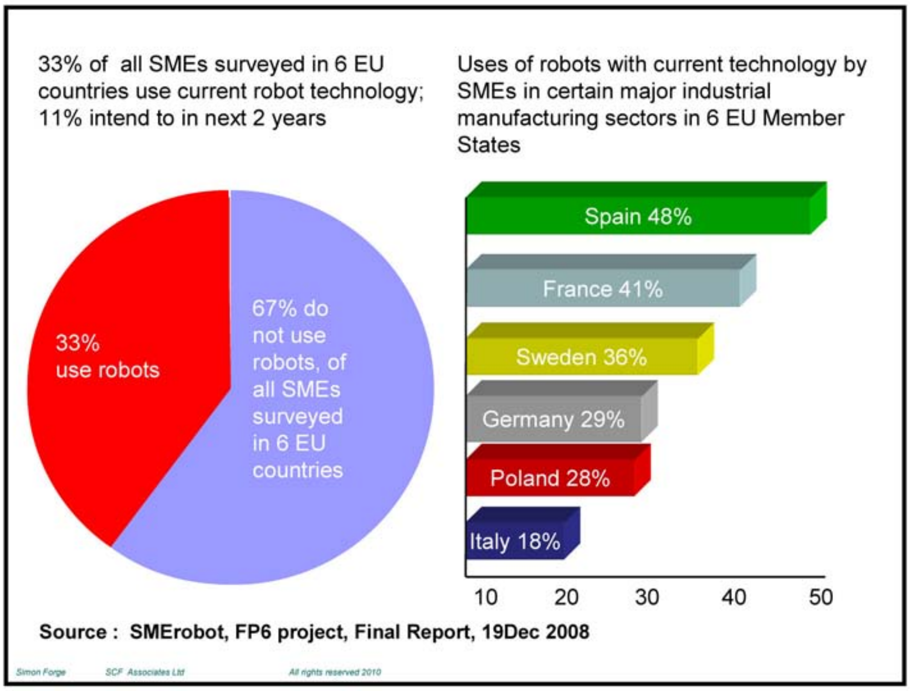
'The food and beverage sector lacks skills, resources and know-how on optimal robot use generally, especially when compared with the car industry.'

In many sub-segments of the SME market are a group of pioneers or early adopters, automating with robots for the first time. For instance, one major robot supplier is investigating opportunities with SMEs in the Formula 1 racing car industry, populated by highly advanced SMEs and potential early adopters of SME robots.

Coincidently, a key SME trend is towards far greater safety in robots (as explored in Chapter 4). This is a significant market driver for SMEs as a new acceptance of robots working together with humans in the same work space and in close proximity would be particularly attractive in

36 SMErobot was a major European Commission initiative for strengthening the competitiveness of small and medium-sized enterprises (SMEs) in manufacturing. In this integrated project, funded by the EU ICT FP6 programme, innovative robot technologies to tackle the needs of SMEs were developed with a large industrial consortium. See http://www.smerobot.org

Figure 3.2: SME use of robots in 2007 in 6 EU countries



smaller companies and would respond to SME needs for robot co-workers.

3.2.4. Size of the market

In order to assess the market opportunity, it is essential to have an idea of the number of robots currently in use in SMEs. There is little data available on this topic, as none of the industry associations have collected data on SMEs in the past. However, the SMErobot project conducted the most detailed survey on SME use in six EU Member States and this is the best information that is available.

The SMErobot survey carried out in 2007-08 compared the annual installation of robots in SMEs in France, Germany, Italy, Poland, Spain and Sweden (Kinkel, 2009) as a percentage of all industrial SMEs interviewed. It is estimated that the survey covered about 20% of all robot installations in the EU (i.e. approximately 5,500 in SMEs, with 27,400 robot installations in total). Of European SME manufacturing companies surveyed, one third were already using industrial robots in 2007. Perhaps this is an unexpectedly high proportion, although it also means that the majority of SMEs, some 67%, do not employ robots. The details of the proportion of industrial SMEs interviewed using robots (as a percentage of total interviewed) are shown in Figure 3.2 with a country breakdown.

A larger proportion of SMEs using robots was found in Spanish and French SMEs than in German, Polish and Swedish manufacturing SMEs. The latter were far closer to the average of 33% but the Italian SME usage rates in terms of the percentage of industrial SMEs using robots were near to half this.[37] Interestingly, the small companies with up to 49 employees were found

37 Lower utilization rates, in terms of the percentage of industrial SMEs using robots in Italy may possibly be due to the higher proportion of SMEs with less than 49 employees (some 37%) resulting in less Italian SMEs seeming to be robot users than SMEs in the other Member States. Also, 23% of Polish companies without robots planned to have them within two years. If such a declaration is true, then there is a large potential for robot suppliers in Poland. This may be verified by the increase in installations/year, in 2007 in all Polish companies, growing by 33% compared to 2006. The survey noted operational stock across all Polish industrial production companies had a massive 2007 growth of 40 %, implying new rather than replacement investments.

in the survey to be slightly less likely to use robots – with an average of 30%, against the overall average of 33%. Four possible factors contribute to this:

- Lower access to capital generally –smaller firms tend to access local banks, while larger enterprises may be more sophisticated with access to bond markets, share issues etc.
- Less internal skills, as fewer staff, possibly less technically competent, especially in software.
- Possible less awareness of technological developments.
- Overall risk factor for a small firm may be higher as capex and opex costs are proportionately larger against revenue.

For the future, at least 11% of the SMEs surveyed by the SMErobot project said that they intended to implement robots in the following two years. Note that the analysis here is for specific industrial sectors.[38]

3.3. The difficulties faced by SMEs in adopting robots

The SME market, as one major European manufacturer gladly noted when interviewed, seems to be finally taking off. This market contrasts with industry convention, of a market for industrial robots aimed at large-scale industrial applications such as car production, for continuous working in mass production volumes. The volume of production has often been a key part of the economic justification for robot use. However, thanks to a steady decline in market prices, robots have become more affordable to small business owners. Other financially attractive options include refurbished robots and leasing arrangements. But there are still some major impediments to take-up.

3.3.1. There are systemic economic problems in the SME segment

SMEs find that adopting robots is not a simple process. Typically the SME segment suffers from:

- Low capitalisation and reducing access to capital in the current financial turmoil.
- Low awareness of technological improvements generally.
- Low technical competence outside core business.
- Generally less-technical competence and possibly standards of education generally.
- Low capability for long term investment, with returns of a progressive nature.

Few SMEs are able to invest if they cannot see short-term returns. This means that they look to relatively rapid solutions to take effect (i.e. less than a year) and which have significant levels of returns to offset the risk of investing (i.e. at least 20% to 50% cost reduction or capability/flexibility increase). Moreover awareness of the use of robotics is highly dependent on the sector of activity. Industrial manufacturing SMEs are more inclined to understand robotics, although they may be doubtful of their real value in their particular field. Moreover the service sector SMEs are much further behind the industrial manufacturing firms, as is also perhaps the robotics industry itself – it is still exploring their specific needs and their market potential.

38 Companies surveyed came from across manufacturing industry, classified into five sector groups according to their typical product complexity, production requirements and their average extent of robot use. Size ranged from at least 20 employees up to 249. The firms were NACE classified as: consumer goods industry – food and textile and leather companies (NACE 15 to 19); producers of wood products (NACE 20); firms in paper and publishing industries (NACE 21 to 22); manufacturers of furniture and musical instruments as well as recycling firms (NACE 36, 37); manufacturers of chemicals and chemical products, rubber and plastic products as well as of other non-metallic mineral products or of basic metals; industrial process industry (NACE 24 to 27); manufacturers of machinery and fabricated metal products (NACE 28, 29); manufacturers of electrical and optical equipment (NACE 30 to 33); manufacturers of transport equipment (NACE 34, 35) – (which traditionally apply robots most intensively and are therefore of special interest).

3.3.2. Barriers of SME ignorance about robotics can hold back wider use

The most commonly encountered barriers are three-fold and are closely linked:

- Ignorance about robots and what they may offer the SME. This implies that more education of the SME market is required on how robotics can be used in the specific vertical sector that the SME competes in. There may well be a lack of understanding of where robotics could fit into the business and how productivity could be augmented. Barriers for the SME segment thus revolve around education of the market – understanding what can be done and then knowledge of how to do it. SMEs need to have confidence in robots delivering productivity – the barrier is education and confidence.
- Lack of skills inside SMEs for supporting robots, especially for programming them. Skill levels are highly variable but an SME is unlikely to know enough about robots to plan their integration, perform the installation and then do regular changes as the working tasks change, which usually implies reprogramming plus routine maintenance. Current technology, which implies the traditional models of industrial robot, are often a step too far in complexity. Thus small businesses face special challenges and needs when deciding to invest in robotics. One fundamental challenge is how to operate every day after buying and installing the robot system. With conventional robotics technology, SMEs face the challenge of attracting and retaining a robot 'champion' who can reprogram the robot cell for new tasks and address technical issues as they arise, or of forming a close reliance on a local systems integrator with that ongoing cost. To quote one large supplier:

  "The large users have their own internal skills base and qualified full-time teams for programming, simulation, set up and then for operational maintenance in production. This is not the case in the SME. A whole support infrastructure may be needed, e.g. for robot programming and operations people, on call for 24x7 operation in some industries. It is not obvious how this can be met. The SME needs experts for both robotics set up and for the industrial process - these two sets of experts must work together to create more productive ideas, with new ways of using robots but ones that will work in a 24 x 7 situation. So we find many SMEs need stronger support (than for large enterprises)".
- The lack of willingness to invest in robotics – this is linked to the factors above but also aggravated by the current economic crisis, making access to funding for a new venture more difficult. This factor is exacerbated by the SME profiles in Europe – some 92% are micro-companies of less than 10 employees (Milne, 2010). SMEs are in deeper difficulties than normal with the current financial crisis. For instance, in Portugal, where in 2005 there were 489,000 SMEs, in 2009 there were only 267,000 left[39] (a 45% reduction) as so many were bankrupted in the recent and continuing financial conditions. Many SMEs lack the facilities internally to set up and run robots and are not offered the finance or facilities to use robotics as a way to augment their production. The financial situation and credit squeeze makes SMEs frightened to invest. Even if they are convinced, there is no access to the capital needed.

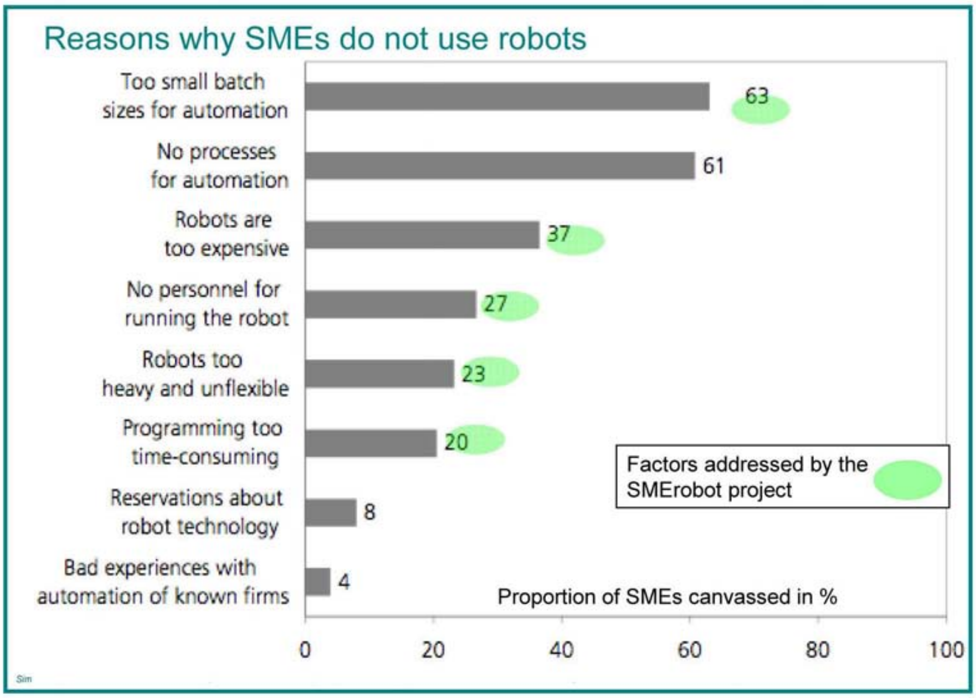
39 According to the head of the largest SME association in Portugal, Augusto Morais (Milne, 2010).

Further barriers are due to:

- The trust that needs to be built up with the supply chain – this is especially important for understanding the value of buying in skills and support, usually via a systems integrator (S/I). This can be seen as hazardous by an SME for two reasons. First the actual length of time and effort to install is not completely determined, as it is with a commercial off-the-shelf product. So this phase requires a fixed price contract to overcome fears of cost overruns. Second is the fear of future high bills if something goes wrong and the S/I must again be called in, and if each time the work plan is changed then the S/I must be called to ensure everything in production works as expected.
- The inability of traditional robot models and technologies to interwork closely with humans in a shared process due to safety hazards – they are too dangerous to work alongside in a shared workspace. Usually, robots have worked in a highly separated space, a caged cell, to avoid dangers of severe injury. But SMEs need human-robot collaboration far more and far closer – SMEs want a team member. They do not have large automated production lines suitable for a car industry type of robot. This co-working issue has legal and liability problems as well as physical injury issues. Who is liable – is it the robot supplier, the installer or SI, the safety systems supplier, the programmer within the company, etc?
- Fears of unemployment by the workforce, if robots are introduced, exacerbated by the threat of the worst recession in Europe for eighty years.

At a more detailed level for the industrial manufacturing SME, major rejection factors are shown in Figure 3.3.

Figure 3.3: Operational rejection factors for industrial SMEs with today's robots



Source: SME robot project, from Final Report, 19Dec 2008, and see www.SMErobot.org, final presentations, Stuttgart, 08 May 2009, Potenziale und Nutzen von Robotersystemenfür KMUs Abschlussveranstaltung. http//www.smerobot.org/final workshop/ (nb some presentations are in English, others in German).

Thus attitudes of the SMEs to robots are a crucial factor in market success. The issue is whether recent advances in robotics engineering meet their special needs adequately. Overall, resolving the problems for SME customers will require addressing:

- The general attitude towards robots and SME levels of education of a robot's capability,
- The core reasons and barriers for rejection of robots in European SMEs,
- Actual uses of today's robots in SMEs – and the future demands in the SME segment,
- Numbers of robots in use in SMEs, which varies across the EU – and why it varies,
- SME plans to invest in robot technologies - and kinds of applications contemplated,
- Potential levels of interest in robots following market education.

3.3.3. Clustering, system integrators, and SME special interest groups can address some of the key problems

What are the ways forward to bring down the barriers?

Obviously, establishing a business plan for investment is often needed to give the confidence to acquire a new robot. This is financed by some robot suppliers, for companies of any size. The productivity gain and other improvements highlighted in the business plan are essential to convince the SME customer.

A key element is the system integrator (S/I). However there are many S/Is for the SME market now – yet, to introduce successful robotics, it is important for the SME market to educate S/Is as to what SMEs need and for the S/Is to educate the SME market on what they are capable of. S/Is must have two sets of skills in general. Just knowing the robot and its integration with the physical environment and specific auxiliary sensing systems for the work task or safety controls is not enough. With SMEs especially, the S/I should know about both the vertical sector and the specific application of the robot in that sector – e.g. for lifting, polishing, welding, etc, as there is likely to be far less experience of robotics in a small SME than in a larger company.

A further useful way forward to overcome these barriers is to encourage interest groups for the SMEs who can share knowledge/ know-how and give information on support required. They also provide help with benchmarking to measure the difference made by robotics. This increases the SME's confidence as they can see that what the sales people for the robot supplier are saying may be true – useful as SMEs may not tend to believe sales people always.

Taking this further is the concept of an industry cluster bringing together various types of player:

- A local group of SME end-users who can share experiences,
- Local SMEs with application domain knowledge, and perhaps the possibility of sharing,
- Suppliers of robots with strong local presence, be they large suppliers or small specialists,
- Technology suppliers for the robot manufacturer and for special items for the end-user,
- A link group to promote use of robots and support first installation through to production.

The clustering approach is quite powerful, as demonstrated by the Swedish Robotdalen cluster (see Box 3.2).

Box 3.2: Robotdalen: introducing robots into SMEs - a regional cluster initiative

Robotdalen (Robot Valley) is an incubator organisation that has introduced robots to over 170 SMEs in Sweden since it was established in 2003. Effectively, Robotdalen has created a regional cluster of robotics development for industrial, field robotics, and health care applications, as well as logistical automation located in mid-Sweden. It draws on local universities to provide students who can work with SMEs to introduce robots, guided by a team of experienced mentors. These teams are tasked with helping SMEs to take up robots by looking at their business processes and proposing solutions.

The fees for doing this consultancy work are paid for by Robotdalen, in order to stimulate the region's competitiveness. Regional growth targets for 2013 are 30 new businesses, 30 new products and 1,000 new jobs. The overall aim is to create regional growth by building upon the local strong industrial and academic traditions and cooperating with all of the companies working in the robotics field.

The incubator provides innovation support to disseminate its techniques and competence across the region. It encourages and participates in R&D projects in SMEs, hospitals, and multinational corporations, such as ABB and Atlas Copco, as well as the local universities of Örebro and Mälardalen. Such developments are generating international interest in Robotdalen and it has initiated collaboration with the American Automation Valley in Detroit, Michigan.

The Giraffe teleconferencing robot for the elderly and disabled. The company moved to Robotdalen from Silicon Valley as the market is better in Sweden while support from the cluster is attractive.

Robotdalen is part of the VINNVÄXT programme, organised by VINNOVA. This programme is its main source of funding, with some partial financing also from the European Commission. VINNOVA, is the Swedish Government Agency for Innovation Systems, which invests in developing Swedish regions with the aim of making them competitive on a global basis. Thus Robotdalen will receive SEK10 million (€1m) annually during the ten-year project period 2003-13, with provision of matching funds from regional actors, which was a funding requirement.

Robotdalen's key strategy is to encourage participation by SME users and robot suppliers in innovation projects, reasoning that its support for ideas will lead to the commercialisation of products and services. Consequently, encouraged by Robotdalen, economic growth in the region is already being driven by a robotics industry supplying industrial and surveillance robots usable by small- and medium-sized businesses. The hope is that robots for medical and healthcare services will also be common soon. To implement this strategy, Robotdalen has concentrated on three main areas:

- Strategic research - specifically robotics for SMEs, e.g. flexible grippers/fixtures; simplified robot programming; faster robot reconfiguration; mobile platforms.
- Industrial projects - for SME users able to exploit robotics with feasibility studies (using local university students and mentors), resulting in the 170+ SMEs being introduced to robots.
- New concepts - 5 new concepts with rapid commercialisation.

Research and development is focused on creating new business opportunities, especially for industrial robots for small and medium-sized companies, as well as in the health care field. A company can either participate in an innovation project in Robotdalen or obtain support for its own ideas.

For more information, see: http://www.robotdalen.se/

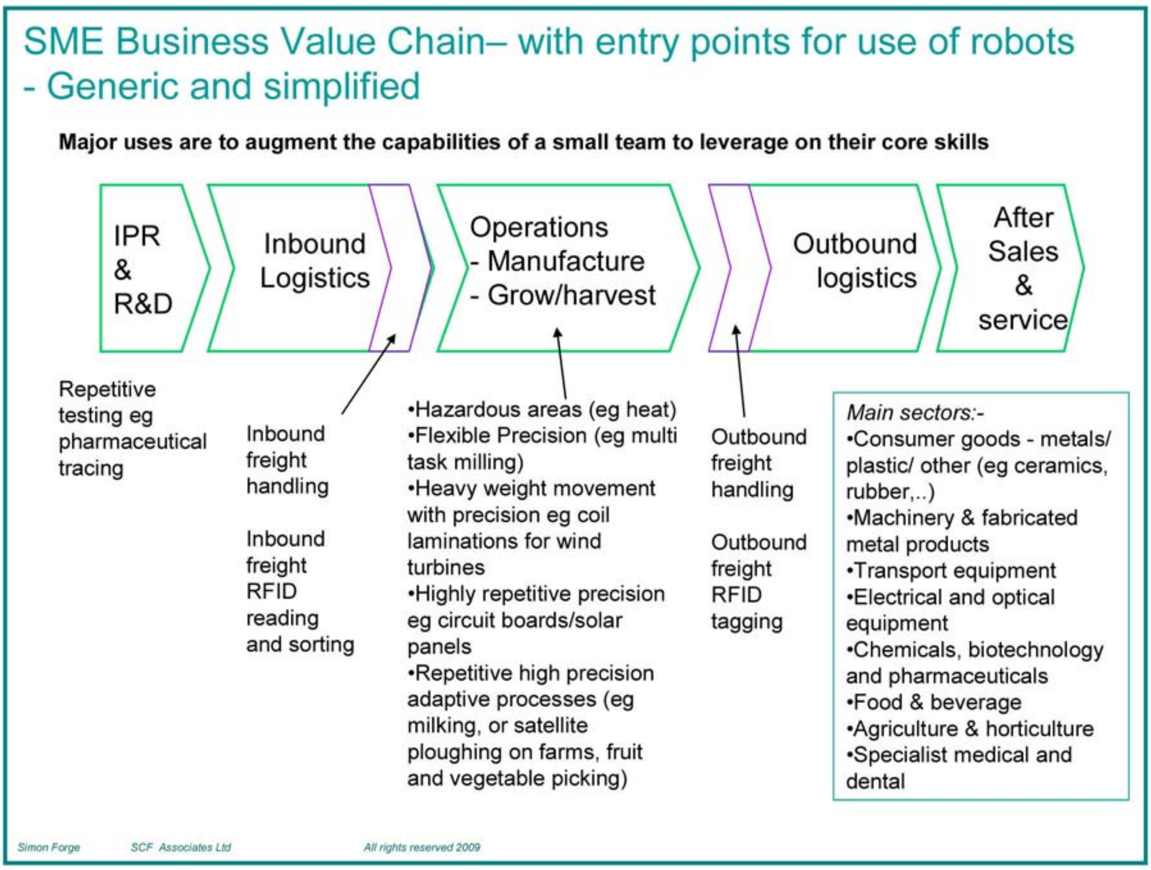
3.4. Where and how robots fit into the SME end-user value chain

Often, robotics only fit in the main production operation of the SME value chain. Robots may also be vital for handling heavy loads inbound or outbound, or for identifying inbound parts or deliveries using barcodes, print and RFID tags, and labelling outgoing produce, e.g. with date and sell by stamps, essential in food, beverage and pharmaceutical SMEs, including farming, etc.

The value chain position for robots is driven by needs in the end-user SME, largely focussed on more cost-effective processes, e.g. for tools selection and fitting in a small manufacturing company, or the transport of heavy materials/ pieces regularly at a rapid pace. As the key SME user segment is still really manufacturing, overall growth is likely to be slow in this segment with the financial crisis, especially for SME suppliers to the auto industry. The main general uses of industrial robots in manufacturing SMEs can be classified, approximately in priority order, as:

- Handling materials, such as stacking, moving items between stations, palletising, etc, which may include picking and recognising random orientations of parts,
- Machine tending – e.g. supplying tools to machine tool,
- Materials and parts processing or treating, such as welding, cutting, soldering, deburring, sealing, or polishing and also coating, dipping or painting,
- A variety of general assembly tasks such as inserting integrated circuits in boards,
- Dismantling with standard procedures, e.g. for recycling processes.

Figure 3.4: How robots fit into an SME value chain



Impacts of robotics across the SME value chain can be generalised, as in Figure 3.4.

From research with SMEs using robots, several key points appear about the place in the value chain of the robot and most of all, what work goes on around it.

Often the robot may not come from a robot supplier but from a supplier of the application, effectively a value added reseller (VAR). For instance, in a metal forming SME for the transport industry in Sweden, a welding robot came from a supplier of the welding equipment, as such applications and tool suppliers act as a market channel for the main robot suppliers. VARs sell the complete equipment, possibly installation with systems integration and commissioning followed by service support, while the robot manufacturer only supplies the base robot, without tools or the auxiliaries. So the net requirement is far more than just a plain robot. In addition are all the robot tools, physical interfaces to other equipment and the guarding or safety fences, plus safety interlocks and any specials that may have to be custom built.

The robot's place in the SME value chain is also tied to the type of work the SME does. Smaller companies are generally more focused on a limited range of tasks and a smaller range of products. Perhaps in contrast to the large production line, robots in the SME are often more used for multi-tasking applications, those requiring several positioners and frequent tool changeovers. Repeatability of robots greatly improves quality here, if tolerance settings are stored.

With offline programming a robot can keep running on current work while the SME is preparing it for new jobs. The flexibility of robots for jobs with smaller lot sizes, where production demand is quite variable, rather than long production runs, makes them preferable to less flexible automated machine tools. Here, robots act as flexible automation systems especially if production entails changing styles and models. As SMEs often make a multitude of items in the same family of products, being able to redeploy the robot for 'nearly the same' job whenever required is useful. Thus, storing the program for a particular task is essential, enabling it to be called up as required, e.g. in machine tending applications where robot systems are handling many different parts. This also suits those small companies with seasonal production. For flexibility, the tooling may reside in the work cells, only called on as needed. To implement all this, managers need to understand the flexibility of a robot and how it can optimise future delivery.

But more generally, robots change more than just productivity. They may transform the SMEs' entire business approach with their flexibility for many types of work at lower cost, enabling custom work more easily. So the firm may be able to expand its market scope to a wider range of work but which is more specialised. This also enables it to be more selective about work undertaken, more specific in tendering for work, so becoming more competitive. The ways in which robots can fit with an SME is not just an EU phenomenon but are general worldwide – we see the same characteristics in other countries overseas, as shown in the box below. This opens up export potential for suppliers of an 'SME-oriented robot'. In the example described in Box 3.3, the emphasis on cost is a primary issue, and refurbished robots are preferred.

Box 3.3: An SME in manufacturing in the USA – robots for cost, flexibility in pricing, safety and productivity

Blue Chip Manufacturing and Sales, of Columbus Ohio, USA, employs 47 staff and typically works with metals - handling U.S. military surplus projects as well as parts for commercial customers. The company offers multiple processes, from machining and fabricating to welding and painting. In 2007 the firm installed two refurbished welding robots from RobotWorx. The robots have gone beyond impacting productivity and savings to transforming the firm's entire business approach.

Recycling used robots for SMEs makes sense to cut costs

The robots, a Motoman K6 and OTC/Miller MR-V6, have given more flexibility, at lower cost so enabling the firm to be more selective about projects. Thus Blue Chip can be more specific when making offers, making the firm more competitive, as it can be more creative in quoting. With a small workforce, the robots also offer a simple way to increase production, making it easier to match demand peaks while saving money. Moreover the robots have improved Blue Chip's work environment. Employees are protected from the fumes, heat, and flash that accompany manual welding applications. The firm is considering another robot - to handle a heavy-lifting task that is a potential hazard for the workers. A key point is that despite all the promise of productivity advantages, it is confidence in support that is the key deciding factor. The firm's director feels confident in taking up robots because he has found a trusted supplier. He has known this supplier for some time, and can rely on crucial help for the SME, especially for know-how about installation and working. Refurbished used robots made sense for this SME as the financial benefits of buying used rather than new robots were evident sooner - each robot paid for itself in a few months. The first refurbished robot purchased was four years old and cost $20,000 (€16k), compared to some $90,000 (€72k) new. A second, newer robot less than a year later cost $60,000 (€48k) compared to $150,000 (€120k) new.

Source: 'Used Robots Give Small Columbus Business a Competitive Edge', Used Robot News, 24 October 2007, www.usedrobots.com

3.5. The SME market potential in the EU

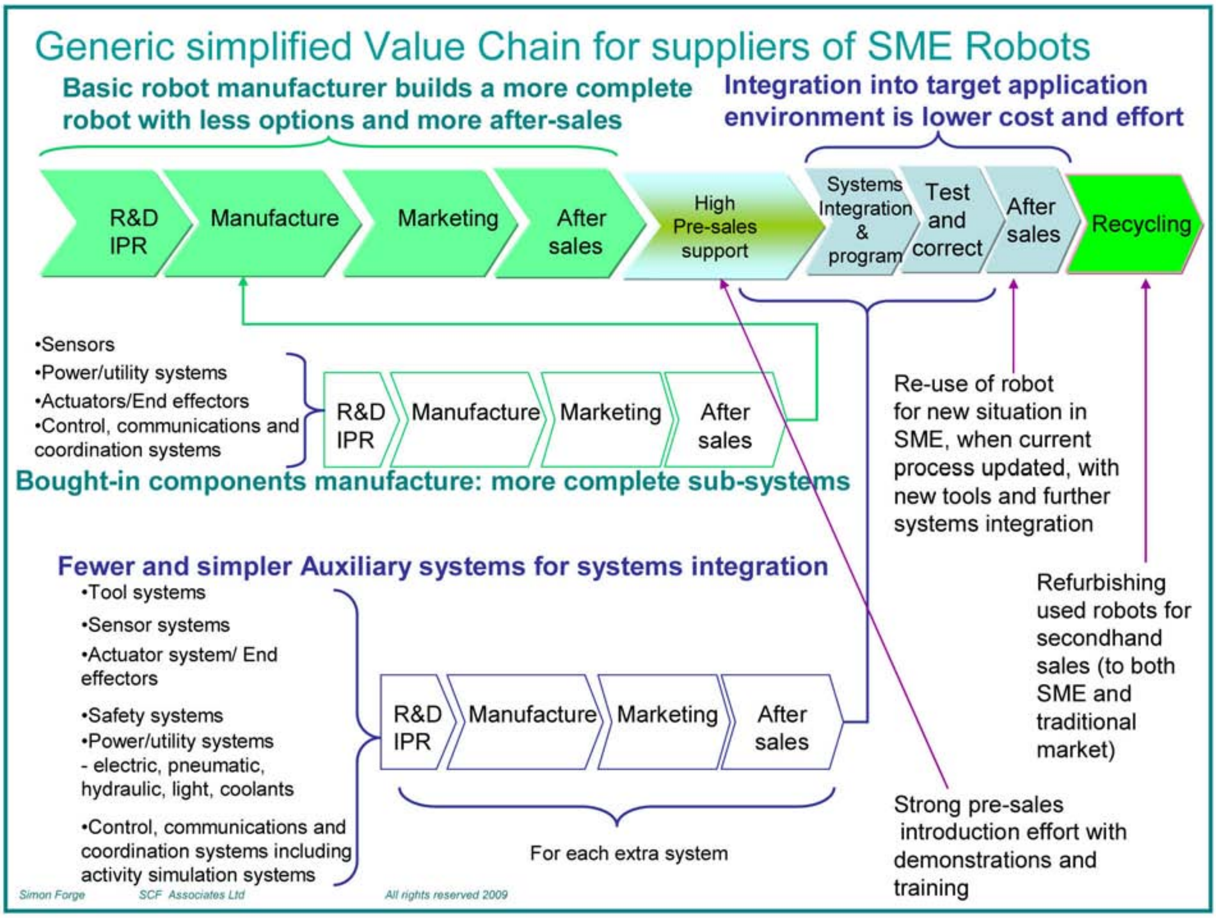
This section analyses future needs of SMEs, new robot designs that would better respond to SME needs, new directions in robot research, and the positioning of the EU industry for the SME market segment.

3.5.1. The future demand side – needs analysis from the supplier's value chain

Seen through the supply-side value chain, shown in Figure 3.5, the SME end-user market shows little basic difference to that for the large industrial robots. However it is instructive in that the conventional value chain must be extended for the SME market:

- First, by the cost factor, in that recycling becomes important. Buying used robots refurbished for sale on the second-hand market may cut capital costs by 40% to 70%.
- Second, the pre-sales effort may be far higher in the SME market, in order to educate, introduce and train, while post-commissioning support requires reduced pricing but will be relied on for the long term as SMEs may never have all the skills in-house. Leasing may also be introduced to cut the capital expenditure (capex) further.

Figure 3.5: Supplier value chain for traditional and new technology SME robot production



3.5.2. Evolving the current generation of robotics technology to suit SMEs

The current state of the art is largely to use existing robots aimed at manufacturing, with their software, for the SME market. These types are supplied by the current players – e.g. ABB, Kuka, Comau, Reis, Gudel, Staubli, etc., from Europe and Fanuc, Denso, Motoman etc., from Japan. However, many suppliers (e.g. Kuka, ABB and Motoman especially) have now evolved a special SME offering in both products and support services, with:

- Lower costs, from planning and procurement across the life cycle,
- Lightweight robots suited to lighter tasks, often found in SMEs,
- Smaller lighter controllers and power supply,
- Support for a business case study to justify investment with lifecycle planning,
- Links to industry specialist S/Is for each major SME category by sector (e.g. food) or application (e.g. welding).

More generally, robot manufacturers are now going to greater lengths to make programming, operating and maintaining robots a simpler and more manageable process. A big challenge is to make a robotic system as user-friendly for the SME customer as possible so that small businesses can overcome the fear of using a robot and not just think of them as highly complicated machines. Robot manufacturers and system integrators may offer training so SMEs can perform maintenance, programming, etc. themselves.

The larger robot manufacturers endorse the strategy of using a system integrator as a prudent move for a small business, who can then rely on the S/I for work cell maintenance if it does not have the in-house expertise to do so on its own. Larger robot suppliers appreciate the S/I as a key channel partner for the SME market segment.

Note that this repeats the distribution model as in other ICT segments for the SME market, such as in application software, computer servers and telecommunications products, i.e. where expertise is often required to accomplish the product sale, both in applications and the vertical sector.[40]

The larger manufacturers may also offer the SME specialised services. For instance, initial set-up may require a CAD type simulation, to get accurate cycle times during the process. This must be done cheaply and an SME does not wish to buy a CAD package for limited use. With standard CAD software today, certain robot manufacturers can offer the setup CAD simulation as a service. This can be done using a shared application (SaaS) over the Internet, avoiding purchase of the CAD simulation software. And it can be done on a global scale – for instance ABB customers in Australia are having CAD simulations done for them from Sweden. The overall impact is to reduce set up time and commissioning, and costs overall as no package purchase in necessary.

3.5.3. Designing robots for the SME market

When the focus is on the SME, new parameters for design appear. These have been highlighted following research by the suppliers and from projects such as SMErobot. Design parameters emerging from this work for an SME robot are outlined in Box 3.4.

As indicated, anything that can reduce the overall lifecycle cost is especially desirable, including reducing the time to produce and install, traditionally a costly process, to be minimised both in complexity and in the time required from expensive experts. One way is to use standard PC-based software as much as possible, with applications downloaded as required. This calls for standardisation of robot sensors and actuators as well as the basic robot platform's software.

Box 3.4: Key design parameters for robots for SMEs

- Robots need to answer a real need for the SME –which requires understanding vertical sectors so the use of robots can gain acceptance through their added value, e.g. productivity or in a wider range of tasks.
- Cost –the overall envelope, from feasibility study to robot purchase to preparation for installation, system integration installation, with testing, final commissioning, programming, reprogramming, maintenance, etc– so reducing both capex and opex. Standards components are important here.
- Safety – a major trend is towards working with humans as a normal condition in a shared workspace on collaborative business processes. This requires major advances in safety, both safety devices and in robot engineering (see next chapter). It can involve integrated collision avoidance systems, whereby the robot brings its protective equipment with it, or it is embedded, so that the extra external complicated safety devices are not needed such as interlocks, motion detectors, security vision systems and light curtains, etc.
- Ease of programming and of reprogramming after a short production cycle, as the frequency of reprogramming may be higher in an SME for new tasks, with programming by non-expert staff e.g. by demonstration, use of language or graphical symbols, perhaps in a few minutes even. Essentially

40 For instance PC support for the print media sector is highly specialised in the applications software – e.g. for page layout, and in storage and network engineering, with complex interfaces to high quality printing.

we are moving from humans understanding robots to robots understanding humans, be it via voice, gestures or graphics. This is one of the major technology advances required, with enormous market entry advantages, as the robot can be installed by a worker, not a specialist.

- Greater flexibility in functions –no longer mono-function. This capability is related to the above point- being easy to adapt, at physical as well as programming levels. This implies a multi-tool robot which can be fitted with various tools e.g. for welding, milling, drilling, polishing, sanding or painting, which can be quickly and safely exchanged to extend functionality –i.e. instead of six specialist robots is one general purpose unit. Moreover, it has the capability to grasp randomly positioned work pieces, e.g. from a box.
- Ease of installation –perhaps by 'plug and play– effectively ease of connection –which requires detection by a configuration module of the functionality being built and perhaps the need for a compatible system complement, e.g. connecting a visual recognition module for accurately placing items to complement a robot arm and a gripper unit has to be joined not just electrically but logically into the controller.
- Extend the main field of application from mass production (e.g. the car industry) to small run-cycles, as typically found in SMEs. Most important here is the creation of an SME worker's 'third hand': i.e. the robot can be used as an assistant or as "third hand" for the worker for assembling or treating parts. Thus the robot arm becomes more of a work appliance, almost like a very advanced electric tool.
- Lighter weight so the robot can easily be moved from place to place. It can thus be utilised for various tasks by simply plugging in and out, the so-called plug and play system.

3.5.4. New directions in robot research

Following the above design parameters, fundamentally different types of robot are emerging from European research and elsewhere, e.g. in the USA in the work by NASA with GM.[41]

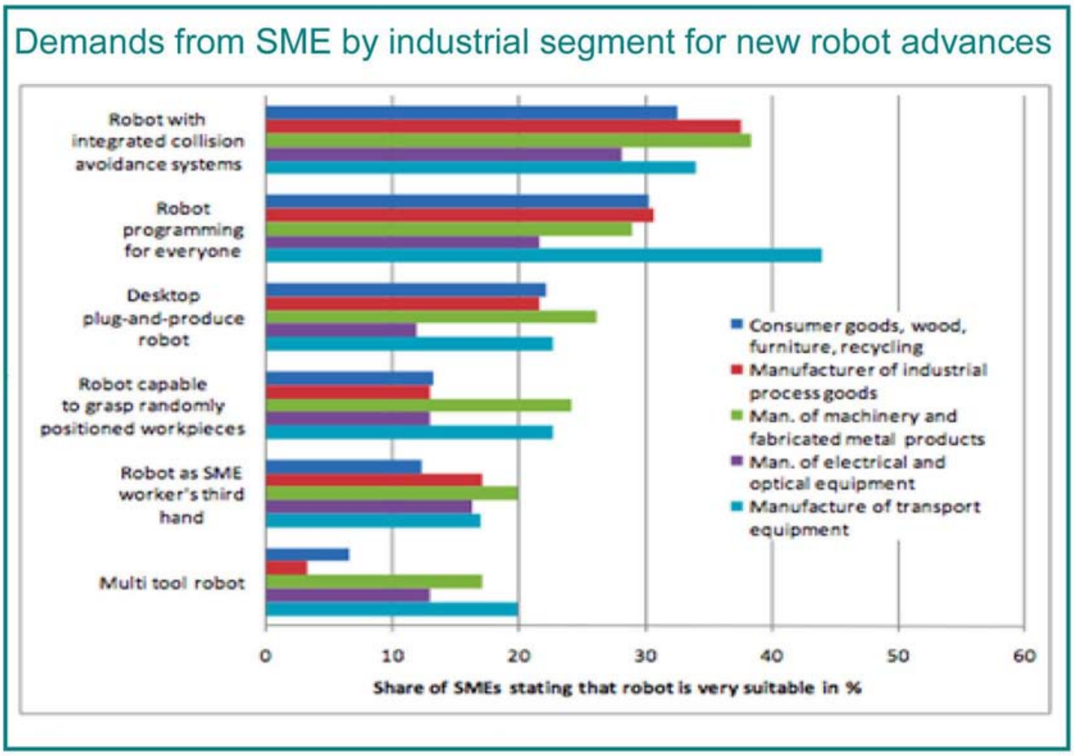
One direction is towards 'soft robots', a topic explored more fully in Chapter 4 on robot safety. This is of particular relevance to the SME market, enabling robot co-operation with humans in the same workspace rather than in a protected cage. A major part of the SMErobot project's research, and its future industrialisation by Kuka and others, is the analysis of this new type. Development concentrates on devices and software control to avoid collisions with humans, for far greater safety in co-working. Simpler programming and far simpler interconnection to other systems (termed 'Plug and Produce' by the project) is a further direction. Other features include new forms of arm actuators to limit the damage in case of collisions, giving an effectively softer robot. The needs analysis carried out by the project SMErobot highlighted a priority for the prospective design features envisaged for the new generation of robot, illustrated in Figure 3.6.

3.5.5. Potential demand in the SME market

To understand the level of demand, it is necessary not just to examine existing robot technologies but potential demand for robots more suited to the SME. For example, the survey conducted by the SMErobot project compared the annual installations of existing technology robots in SMEs in six selected EU countries with the installations for all sizes of company. With approximately 20% of all installations already being in SMEs, the project estimated future SME robot potential would increase, by a factor of 20% to 100% of the initial survey results (for 2007) before saturation with the current types of robot. This was based on survey findings that more than a quarter of SMEs in the selected countries were planning to invest further in robots, using current types of robot.

41 NASA and General Motors have unveiled Robonaut 2, or R2, developed jointly as a robotic assistant that works alongside humans, whether astronauts in space or workers at GM's manufacturing plants. The R2 will perform its first tasks in zero gravity when blasted into space in November 2010 aboard the Space Shuttle Discovery. See http://www.nasa.gov/topics/technology/features/robonaut.html

Figure 3.6: Features demanded by different SME industrial segments



Source: SMErobot, FP6 project, Final Report, 19Dec 2008, also see www.SMErobot.org, final presentations, Stuttgart, 08 May 2009.

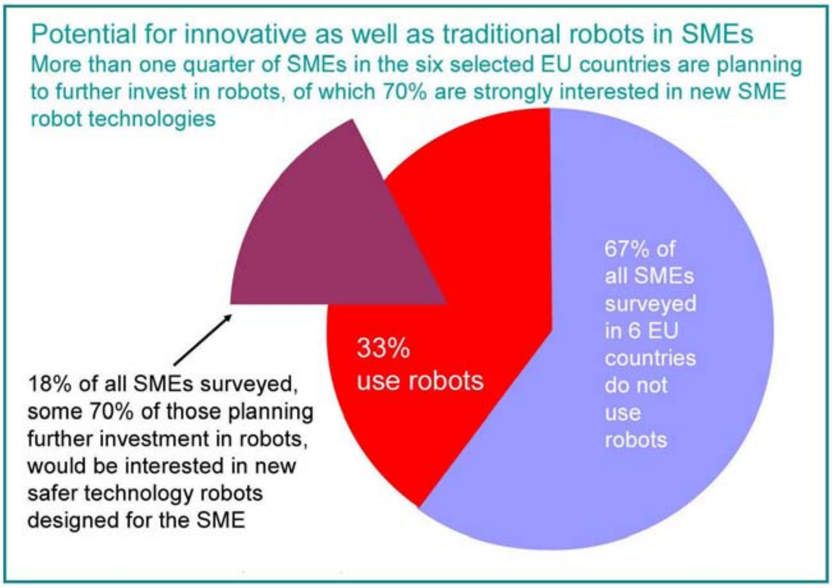
The survey went on to test the demand for new robotics technologies designed specifically for SMEs. The project developed its own range of SME features which it then tested out in the market survey. It found that, of the quarter of SMEs in the selected countries planning to further invest in robots, some 70% are strongly interested in the SME robot technologies suggested. This is 18% of all SMEs interviewed, as shown in Figure 3.7. Overall, there seems to be significant user potential for innovative robots on top of the traditional robots sold to European SMEs.

Expectations that the development of SME robot technologies could lead to a significant expansion of robot use in European SMEs seem to be realistic. New technical developments for SMEs are not yet available on the market, although suppliers such as Kuka and others, following this FP6 project, are preparing for a new generation of technology. With further assessment using other studies across the surveyed countries, the SMErobot project found user potentials of approximately 6,500 SMEs sales per year (some 18% increase), but with higher uncertainty in Spain and Poland. Overall, the estimated potential of future SMErobot user appeared to be higher than initially expected. In conclusion, there seems to be a significant potential new user base.

3.5.6. Industry positioning for this new segment

Competitive behaviour of the major players in this segment is perhaps still too early to define, although leaders in Europe such as ABB with its lighter SME targeted robot and Kuka with its developments for segment in concert with the SMErobot project signal the way. Comparing EU players against the rest of the world, it certainly appears that the research projects going on in the EU might catalyse a lead position. However, the emphasis in Japan on domestic service robots has also led to some SME type developments (e.g. an exoskeleton for farmers enabling them

Figure 3.7: Potential for innovative as well as traditional robots in European SMEs



Source: SMErobot, FP6 project, Final Report, 19Dec 2008, also see www.SMErobot.org, final presentations, Stuttgart, 08 May 2009.

to lift much heavier weights and perform tough manual labour for far longer). Naturally the major Japanese suppliers also have the SME segment as a target for the marketing of industrial type robotics worldwide. The USA is highly conscious of the SME segment as a specific market and has been for some time (Brumson, 2003), with the main suppliers serving it with industrial robots and a strong refurbishment segment for second-hand sales, in order to lower costs.[42] All of the leading Japanese and American brands appear in the USA's refurbishment market.

Examining the strategic position of EU suppliers against the other globally and region-dominant suppliers by comparing positions along the value chain, for SMEs, Europe appears as fairly strongly positioned:

- The major EU suppliers of complete robots are all well aware of the segment and developing products for it. They are well positioned both to supply the EU market and to compete globally.
- On the systems integration and support services side, local S/Is are strong. More S/Is are appearing for the SME segment, from domain experts in applications (e.g. welding). And traditional S/Is being encouraged to enter the SME market, due to SME needs for an eco-system of support, which they need far more than the traditional large enterprises. On the supply-side, the large robot suppliers (both EU suppliers and those from Asia and present in Europe) are also building their SME marketing operations with co-marketing and training of S/Is for the SME market on their products. They build portfolios of S/Is by vertical industry and by application segment, just as is usual for the application software industry. In turn, the larger S/Is (e.g. Geku, UK) try to have multiple supplier partnerships in order to offer the end-user a range of robots.
- On what might be termed the components side, we see a bifurcation. Hardware components tend to be sourced worldwide as for the large enterprise models, as this is still a market of scaled down large machines rather than special models so far. This

42 The USA stands out as providing the same recycling segment as for other high capex ICT products, from mainframes and large Unix servers to the high-end routers, providing software, upgrades and after sales support.

is likely to continue, with many special components being sourced from Asia due to cost advantages of volume scale production. Much software, especially for the specialist add-ons is of European origin. It tends to have higher added value than hardware elements.

3.5.7. Beyond traditional industrial manufacture

Key user segments for growth may not be the traditional ones, e.g. industrial activities for the auto sector. From experience with the Swedish Robotdalen cluster and others, potential lies with a range of diverse new markets demanding novel applications of robots in SMEs. For instance, these new segments for manufacturing robots include:

- Specialist high technology areas – especially in the green industries: e.g.:
  - Solar panels - start-up SMEs are now appearing. Robots are used for placing large arrays of printed photovoltaic circuits into the panel, and
  - Generators and parts for wind turbines, for assembly as well as manufacture.

- Applications arising from new trends in traditional industries, such as construction, which have not previously used robots widely in the EU. One example is production of prefabricated wooden house kits. This is a growing industry in Nordic countries, especially Sweden, which has some twenty manufacturers, often small, as well as larger firms. This is likely to seed a new set of system integrators for the robots for the wooden house kit manufacture.

- Certain traditional SME production sectors that have not used robots until now:
  - Agriculture for animal husbandry, e.g. Lely milking machine (see Box 3.5),
  - Agriculture/horticulture for crop cultivation – ploughing, vineyard tending and harvesting; crop monitoring for vigour with UAVs.

An example in agriculture is shown in Box 3.5. It is sold to all sizes of farm and especially important for the small farm, where milking cows is a relatively large burden for a small staff.

3.5.8. SMEs in the service sector

One expectation encountered in Scandinavia and the UK is for professional service robot sales to the ambient assisted living market to become a major opportunity. With increasing demands for elder care, for the disabled and rehabilitation of those with health problems, this may become a growth area for new types of robot. They would be supplied to care organisations, many of whom may be local providers and quite small as well as the large state organisations. Examples are Giraff in Sweden for videoconferencing in the home,[43] and also Zoom, a Swedish start-up, with a potential joint venture with Toyota for an all-terrain wheelchair for disabled people to access to countryside freely and outdoor sports such as golf.

Note that for the above types of service robot there is a crossover effect– sales of robots with features aimed at the SME market in terms of safety for co-working and ease of programming are just the features sought for the care market, for general elderly care and health care, and for the nascent domestic service sector, for consumers. So eventually SME robots could perhaps open up far wider applications in the professional services and consumer markets.

3.5.9. In summary

Although there is an opportunity for the European robotics industry in the SME segment, it is distinctly different to the traditional robot market and has critical barriers to be overcome.

43 http://www.giraff.org/

Box 3.5: A new direction in SME robotics for agricultural SMEs: dairy farms

Lely of the Netherlands has pioneered automated voluntary milking systems over the past 20 years. Milking by the robot is initiated by the cow, not the farmer, so that a cow may be milked more frequently –typically three times rather than twice per day, to follow a cow's biorhythms. There are now 9000 such robots operating worldwide, averaging 160 milkings per day per robot –with each milking taking an average of 8 minutes.

The first step is identification of each animal by electronic tag. The milking robot gathers details on milk yield and quality, animal health condition, weight and feed requirements, behaviour and productivity for each animal. It also analyses protein and fat content of milk, conductivity, temperature, colour and presence of impurities e.g. water, blood, etc. Biomedical indicators such as quantities of white blood cells are monitored as metrics of health and infection resistance, enabling the farmer to anticipate health problems before they become more serious. The robot can signal when key parameters are at a threshold for one animal or the herd, communicated to a mobile phone by SMS. A weighing floor is part of the installation to check weight over time for every animal.

The robots also can control feed with high quality fodder given while milking. This also acts as an incentive to the cow to be milked. Its content can be individually controlled, based on the yield parameters and dynamic feeding for each animal, so optimising milk production. Robot positioning for milking relies on triple scanning lasers for positioning is used. Lasers are best in environments where camera lenses can get covered in dirt. Overall the financial benefits are in savings on labour costs plus profits from higher yields, which offset the price of around €120,000 per milking machine. A better milk yield example is a family farm in Finland with a 28% increase. Animal yield improves with better animal health and well-being – as animals less harassed with more control over milking as its is voluntary while better quality milk is given at lower cost and less work for the farmer.

Source: Greenaway, 2010.

The major difference is the higher level of dependence on an ecosystem, which goes beyond the main robot suppliers. As identified in the Robotdalen initiative and also by a Taiwan government paper (Ministry of Economic Affairs, 2008), the first crucial market catalyst is the level of support available for SME end-users. Support is needed to educate the SME and then help to find the right solution, with system integration and training – as co-ordinated by Robotdalen for instance. This initiative, and the SMErobot project, also emphasised business-case tools, especially lifecycle costing (Kinkel, 2009), to show the value against a purely manual solution.

Thus, success lies in a co-ordinated micro-scaled SME network, putting together SME end-users with a robotics demonstration, supply and integration eco-system. It requires an active local/national/EU marketing and public relations campaign to build momentum for successful dissemination, with an SME focused campaign of robotics information, with events for SMEs and SME interest groups, as well as media communications (special interest group websites, TV, podcasts, papers, journals, videos, radio all forms of publications, etc). The step-by-step market building process could be seen as:

1. Locate and encourage SME 'early adopters' as demonstrators.
2. Encourage and introduce SME system integrators or VARs; they form the interface between end-users and technology developers and the suppliers.
3. Use local and national SME campaigns with the SME industry organisations (e.g.

CETIM in France) and interest groups as a dissemination mechanism.

4. Through all these and other publicity channels build a campaign, with a series of SME robot demonstrator showcases to co-develop technical solutions for typical SME end-user problems, in order to convince SMEs beyond the 'early adopters'.

The second crucial catalyst is a technical one –to change the form of robot to towards what the SME needs: one that is cheaper, easy to integrate and reprogram, that can interwork with humans and that has reduced external safety requirements due to its internal safety features.

4. The new paradigm in robotics safety

4.1. Introduction

Assuring safety has always been important to the robotics industry but it becomes even more critical for future growth in new application areas. In traditional industrial settings, safety is assured through separation of humans and robots as far as possible, through placing robots in protective work cells. However, with more and more applications envisaged where robots either work in close proximity to, or serve, humans, a completely different approach to safety is needed.

This chapter explores the safety problems associated with robots and the current regulatory framework. The existing approach to safety is examined – for this will continue to be relevant in mass production applications – and the current market and the value chain is described. The chapter then goes on to consider new directions in robot safety associated with robotics for co-working.

The new approach to safety borrows from road vehicle safety by first building a picture of how injuries occur and their extent. This is leading to the design of new robots which are lighter, softer and more controllable, such that any impacts that do occur are much less damaging than those associated with traditional industrial robots. The chapter assesses the market opportunity afforded by this new approach to safety.

4.2. The safety problem and its regulatory framework

4.2.1. What is the safety problem with robots?

Ensuring safety is a key requirement for all robots (Bonney and Yong, 1985). Robots can move quickly over considerable distances and so pose significant safety problems. Owing to their weight and the power required to move that weight rapidly and precisely, they can become quite formidable machines.[44]

Safety is key because without confidence that robots will not harm humans, their application will remain limited (Graf and Hägele, 2001). The need for safety applies not just to traditional industrial types but to any type of robot. A basic requirement for service robots, for instance, is to ensure that they do not fall on or collide with the people they are supposed to be serving. The traditional approach to safety for robots has followed on from machine tools. This places emphasis on hazard identification and risk assessment in setting up robots and providing physical safeguards to separate robots from humans as much as possible to minimise the possibility of collision. However, if the potential of robotics applications in new situations is to be fully realised, e.g. in SMEs and in service and domestic environments, then a new way of thinking about robot safety will be needed.

Robot safety problems have been considered since 1940 when Isaac Asimov proposed that robots should be governed by the Three Laws of Robotics, which would be designed to prevent robots from harming people either through action or inaction, or inflicting self-harm (Asimov, 1940). Although they have remained in the field of fiction until now, such guiding laws are still relevant and useful. Despite improved safety measures over the past few decades, robots continue to be involved in accidents. In

44 In 1979, Robert Williams, a 25-year-old Ford Motor assembly line worker, was killed on the job in a Flat Rock, Michigan, casting plant, in the first recorded human death by robot (http://www.wired.com/thisdayintech/2010/01/0125robot-kills-worker/)

2005, for instance, there were 77 robot-related accidents in the UK (The Economist, 2006). Analysis of accidents shows that the majority may be connected with some form of programming of the robot that provokes unexpected movements (Clark et al, 1999).

However, to apply Asimov's 'laws' would require a robot to have some form of almost human-like intelligence, absent in today's robots while the laws themselves can produce unintended consequences, as demonstrated in Asimov's fiction. But their concept is still useful for design as they encapsulate commonsense principles already applied in the design of most modern appliances, both domestic and industrial. Every lawn mower, electric kettle and mobile phone is designed to minimise the risk of causing injury. Yet people still manage to lose fingers, electrocute themselves, or even fall out of windows, for instance, in an effort to get a better mobile handset signal. At the very least, robots must meet safety standards that cover existing consumer and industrial products.

A key question is whether new, robot-specific rules are needed and, if so, what they should comprise. As already indicated, the traditional approach pursued by the robotics industry has been to carefully separate the robot from the rest of the workforce (Clark et al, 1999). However, this strategy is gradually breaking down under the influence of two trends:

- The growing possibility of robot-human co-working in industrial environments with the robot as helper, even as a third hand.
- The potential for service robots in domestic, health care and other environments.

In both these cases, robots cannot be isolated in a cage as in a traditional industrial robot work cell. As this report has already noted, applications are growing in new environments such as agriculture and food processing (milking robots), for surgical procedures (e.g. the da Vinci surgical robot), and in simple domestic situations, (e.g. the iRobot Roomba vacuum cleaner with over three million units sold).

Thus, the desire to utilise robotics in new situations is increasingly focusing attention on human-robot interaction, including safety aspects. For instance, the Strategic Research Agenda for robotics in Europe developed by EUROP, the European Robotics Technology Platform, forecasts greater cooperation between robots and humans in industrial, professional and domestic service situations (EUROP, 2009). The trend has caught the attention of 'robo-ethicists', who have met regularly since 2006, announcing their initial findings in March 2006 at the European Robotics Symposium in Palermo with safety as a leading concern. They ask some basic questions on safety, e.g. should robots that are strong enough or heavy enough to crush people be allowed into homes?[45]

Safety needs to take into account both hardware and increasingly software, which controls movement, by applying safety-critical computing.[46] One approach is to program robots to avoid contact with people altogether and thus avoid collisions. Building in redundancy by adding backup systems helps to assure safety but complete safety is impossible owing to the unpredictable nature of human behaviour (e.g. a human accidentally tripping over a robot and hurting themselves). Moreover, software may sometimes behave in unexpected ways, especially with the aging of physical components such as sensors and actuators (The Economist, 2006).

The examples mentioned above raise difficult legal problems for the industry over liability and it is particularly because of this that the question of new robot-specific safety rules and regulations are needed. 'Right now, no insurance company is prepared to insure

45 Presentation by Henrik Christensen, of the Swedish Royal Institute of Technology, Stockholm, Sweden, and chairman of the European Robotics Network at the EURON Roboethics conference, Genoa, February 2006.
46 Interview, Ken Young, Warwick Manufacturing Group.

robots', says Tokyo University's Dr Hirochika Inoue (The Economist, 2006). Although existing regulations and product liability laws address much of the safety and liability requirements, the issue is whether robots are sufficiently different to deserve special regulation. Robot safety is likely to first be tested in the civil courts under matters of product liability, especially as finding insurance companies prepared to insure robots may be difficult.

Making sure robots are safe will be critical for their wider deployment. So what any new regulation should say, especially on liability, is crucial. A particularly difficult dilemma is if learnt behaviour becomes the norm. If a robot is autonomous and capable of learning, can its designer be held responsible for all its actions? Today the answer is generally affirmative. But as robots grow in complexity and autonomy, the legal liability issues become less clear-cut.

The widening of robot domains of usage is already sparking new perspectives on safety regulation. In May 2006, Japan's Ministry of Trade and Industry announced a first set of safety guidelines for home and office robots. In Japan, robots are now required to:

- Have sensors to help them avoid collisions with humans,
- Be made from soft and light materials to minimise harm if a collision does occur,
- Have an emergency shut-off button.

4.2.2. Regulatory framework – standards, directives

Standards are the most important means of addressing and solving safety problems in the workplace. Thus of key importance in realising the potential of robots is a move to standards for safety. Robots will have to be certified for safety if large-scale implementation is ever to happen. Note that in Europe, there are currently no specific regulations outside of industry (i.e. in the home) that apply to robots. It means that robot manufacturers are going to be conservative, as the last thing suppliers want is robots causing accidents and adversely affecting a nascent market.

Safety standards for robots have grown out of industrial machinery standards, as well as product safety. Typically industrial robots have been used in far more structured environments than those required for human workers. The origins of safety standards positioned human-robot separation in the workplace as the cornerstone of safety. In general robot standards have presented a well defined situation in which well established national standards (e.g. ANSI-RIA R15.06-1986 for the USA, CSA Z434: 2003 in Canada, DIN ICS53 in Germany, etc) are collected and harmonised, e.g. for the latter set into the ISO 10218 standard.

However, industrial robotics safety standards are currently undergoing an evolutionary change to cope with shared workspaces between robots and humans and types of technology in use (Alami et al, 2006). In 2002 the ISO committee (TC184/SC2) responsible for the 10218 standard voted to revise the 1992 edition. Work has been gradually turning what started as a simple harmonisation effort into a genuine development effort introducing new concepts into the world of industrial robot safety. The revised ISO 10218 ('Robots for Industrial Environment –Safety') is a two-part document. Part 1, the initial updated standard, published in 2006 and entitled 'Design, Construction and Installation', is intended to be compliant with the views of the robot manufacturer; it specifies requirements and provides guidance for the assurance of safety in design and construction of the robot itself, not the entire robot system. Part 2, ISO 10218-2, addresses work place safety requirements being directed more to the end-user, 'Application and Use of Robots in the Work Place', for robots and robot systems integration. Now undergoing development, it is expected to be published in 2011, to cover the integration and installation of a robot system or cell, with a comprehensive set of requirements for robot safety.

Box 4.1: Overview of standards by region

International: Important safety standards are those ISO standards concerning robots:
- ISO 10218 (industrial robots, published) Parts 1 and 2 (to be published)
- ISO/CD 13482 (personal care robots, currently being developed).

These standards refer to the general ISO Machine Directive and to ISO 13849 (Safety Related Parts of Control Systems), where safety integrity levels (SILs) and performance levels (PLs) for industrial automation are defined.

EU: In the EU, product safety issues are regulated in the EC Product Directives. These are directives on a general level for "products" as well as for "machinery" and have more or less to be followed in order to get a CE certificate, which is the permission to sell the product in Europe. See, for instance, The General Product Safety Directive :
http://ec.europa.eu/consumers/safety/prod_legis/index_en.htm.

Other relevant robotic EU standards and Directives are:
- EN ISO 13849 New principles for machine safety (that replaced EN-945 -1)
- European Machinery Directive (EMD):

The safety of robots is regulated by the Machinery Directive, originally adopted in 1989. A revised Machinery Directive 2006/42/EC has been applicable since the end of 2009.[47] The Directive is innovation-friendly, since its requirements are limited to the essential health and safety requirements that manufacturers must apply when designing and manufacturing their products. Technical specifications to help manufacturers apply the general objectives set by the Directive to particular categories of machinery are provided by European harmonized standards. Application of these standards is voluntary, but confers a presumption of conformity with the essential health and safety requirements they cover.
The most important harmonised standard for industrial robots, EN ISO 10218-1, is, as its title indicates, both a European and International standard, developed in cooperation by the European Committee for standardisation, CEN and the International Standardisation Organisation, ISO. This creates a particularly favourable situation for global trade in robots.
The Machinery Directive also provides for a flexible system of conformity assessment since, for most robots, the conformity of the machinery can be assessed by the manufacturer itself, without obligatory recourse to a third-party conformity assessment body.

North America: USA: Occupational Safety and Health Administration:
- OSHA Guide 3170-2007 – safeguarding equipment and protecting employees from amputations
  USA: ANSI standards:
- B11.TR4- 2004 Selection of programmable electronic systems (PES/PLC) for machine tools
- B11.TR3- 2000 Risk assessment and risk reduction- a guide to estimate, evaluate and reduce risks with machine tools
- B11.19-2003 Performance criteria for safeguarding

USA: The Robotics Industry of America (RIA) also has specific standards, generally more stringent.
Canada: CSA Z434 Industrial robots and robot systems- general safety requirements.

Note that other regulations on safety may also apply by function and by country, e.g. in the UK, for lifting robots for handling and palletising – Lifting Operations and Lifting Equipment Regulations and also Provision and Use of Work Equipment Regulations (PUWER),[48] as well as UK Health and Safety Guidelines 2000 – HSG 43 'Industrial robot safety'. In the USA, the National Fire Protection Association (NFPA) 79 standard covers industrial machinery safety. Recent revisions of NFPA 79 have pushed implementation of programmable safety systems, with PLCs and digital buses.

47 See: http://ec.europa.eu/enterprise/sectors/mechanical/documents/legislation/machinery/
48 Murgatroyd, Ian (Pilz Automation Technology) Setting the Standard, Automation & Robotics, 2008, see also UK HSE website, www.hse.gov.uk/equipment/legislation/htm

The most fundamental changes in such new standards are in:

- *Safeguarding and clearances* – a major step towards completely removing the requirement for safeguarding, provided that appropriate safety capabilities and features are possessed by the robot control system itself.
- *New modes of robotic operation* – standards for synchronised robot control,[49] mobile robots mounted on automated guided vehicles (AGVs), and "assisting robots" which work in a collaborative workspace with the operator.[50]
- *Control system types* – former standards placed reliance upon hardwired electromagnetic components; current versions allow safety-related control circuitry to use state-of-the-art electronic, programmable, and network based technology (including wireless).

In parallel, the USA ANSI with the Robotics Industry Association has established the T-15 committee, to update the existing ANSI/RIA R15.06, to publish a draft safety standard for robotics interacting with humans, with the major points being:

- *Risk assessments in place of fixed rules* – to identify and mitigate risks in proportion to their seriousness and probability;
- *Safety critical software* – for software and firmware-based controllers, any single component failure leads to the shutdown of the system in a safe state. Such a degree of safety may be achieved by using microprocessor redundancy, microprocessor diversity, and self-checking;
- *First safety requirements for four major new robotic technologies:* cableless teach pendants, human-robot collaboration, robot-to-robot synchronization and vision-based safeguarding.

The wide range of standards that apply to robots now reflect this, as described in Box 4.1.

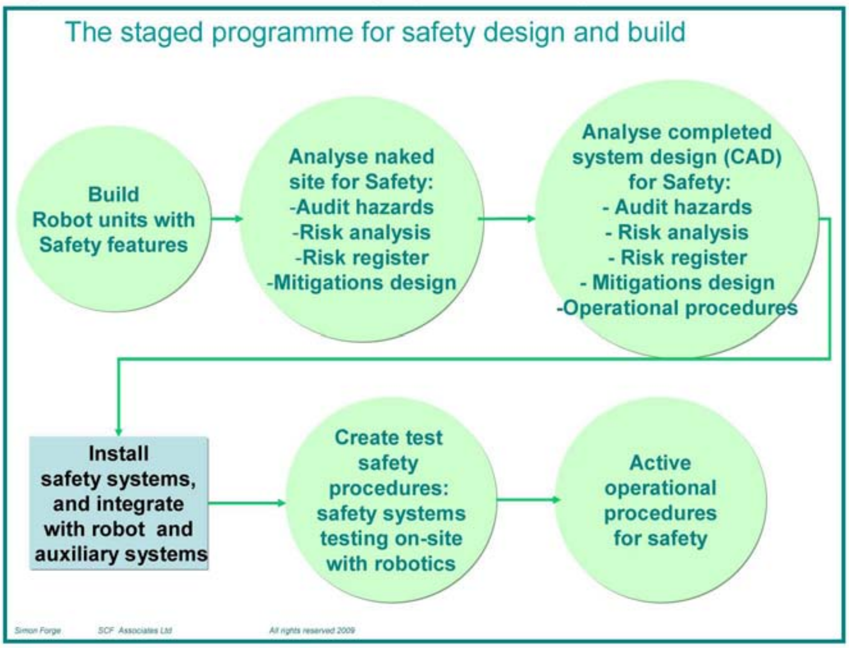
4.3. The robotics safety sector in the EU and its value chain

The current robotics safety market in the EU is based on the widespread current practice of separating robots from humans. This is achieved by building a physical protecting barrier around the robot cell, consisting of cages or barriers plus emergency stops, safety interlocks, safety plugs and failsafe switches with detection of moving objects by visual, infra red or sonic motion detection systems. Such systems are often made redundant for failsafe reasons – for instance one installation based on a Pilz visual system uses three cameras. Generally robot safeguarding has grown up since the 1970s to be a major component system in its own right, with a series of safety measures:

- Work cell design for safety, with hazard identification, risk analysis, etc.
- Perimeter barriers, screens and pens to halt entry of humans, with alarms for interference.
- Monitoring systems with visual monitors and reporting of alarms to remote surveillance centres.
- Intelligent collision avoidance systems, often employing visual or other motion detectors. These may be built from collision situation detection and anticipation, by sensing visually or otherwise, or by mechanically detecting a collision and stopping/withdrawing from the obstruction as soon as encountered; physical sensors may perform this function.

49 Synchronized robots have two robot arms and one controller (e.g. some Motoman models and others).
50 Physical human-robot interworking (pHRI) is sometimes termed Interaction in Anthropic Domains (IADs).

Figure 4.1: The process for robotics safety systems setup



- Where possible, placing of programming devices and the electronic controller/computer outside the robot cell with monitoring by CCTV inside the cell of reactions by the robot to program changes.
- Training of personnel, following a targeted selection process.
- External warning signals and high visibility signs about the dangers.

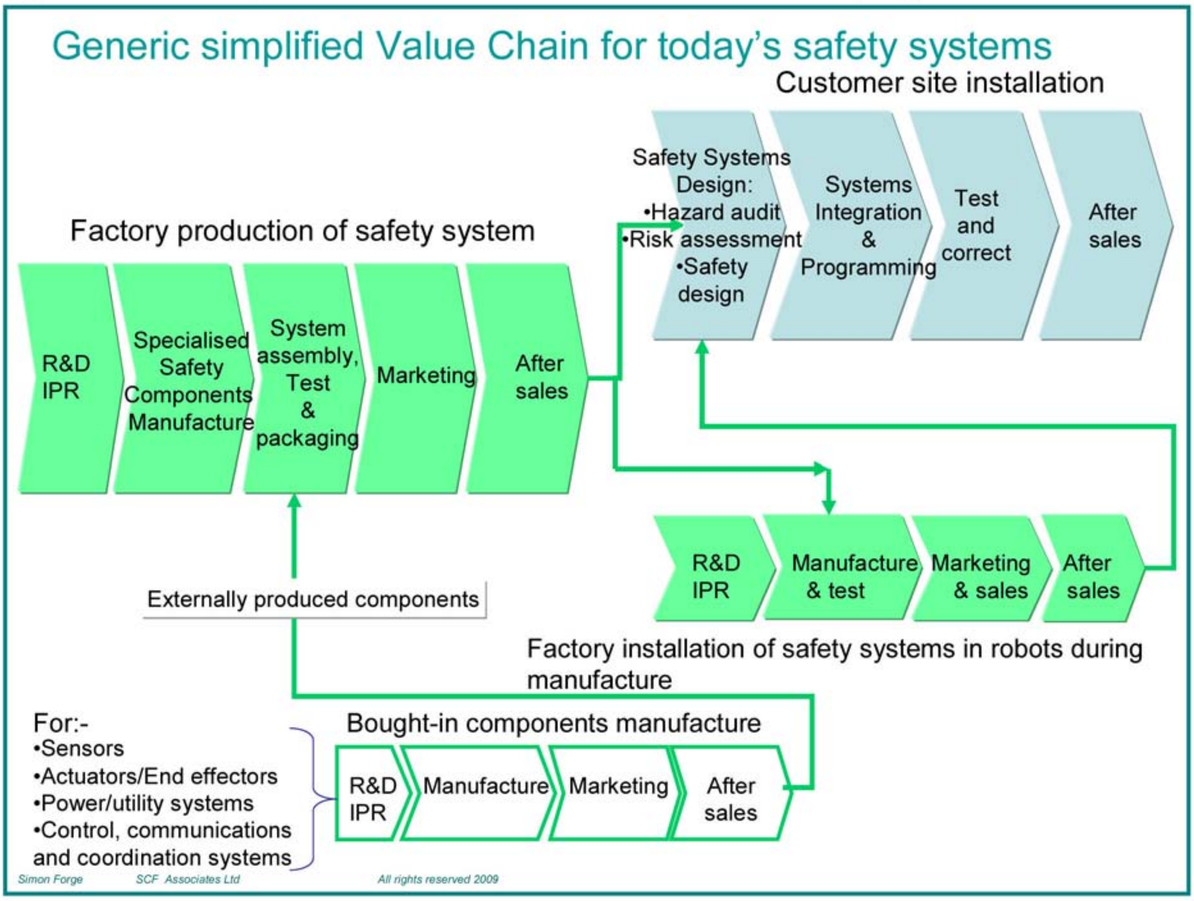
Most industrial robots have a ‘teaching’ mode whereby repetitive activities can be programmed by a human moving the robot arm and recording each position, so that when the robot ‘plays back’ the sequence of recorded operations, the task is performed. Naturally, this can be a hazardous operation and various disabling and temporary lockouts for safety are used. The typical overall industry safety set up scheme for industrial robotisation is shown in Figure 4.1.

The conventional safety systems market is thus a substantial part of the robotics industry, dominated by a small number of major players who provide the base components and systems with a wide range of technologies – mechanical, electrical, electronic and with sophisticated signal processing for roles such as visual recognition of humans, plus simpler movement detection systems which may be infrared, ultrasound, lidar, etc. The major players are well established with a background in machine safety protection going back decades. They see robotics as just one of many market segments they serve.

The two leading European suppliers of specialist safety components and systems are both German – Pilz AG and Sick AG. They supply vision detection cameras, light curtains, interlocks on power, safety mats, emergency (e) stops, and an increasing range of microprocessor based systems. Most of the safeguarding they supply falls into one of the categories of:

- Perimeter safeguarding and interlocked access gates,
- Alternative protective measures for minor servicing,
- Control of hazardous energy,
- Point of operation/operator interfaces,
- Safety guarding of entry points for material flow in and out of the cell.

Figure 4.2: Industry value chain for the conventional robot safety segment



But overall, the safety industry value chain can be seen as having two parts – the manufacture of systems and components and secondly their integration, as shown in Figure 4.2 in the value chain analysis for the robotics safety segment.

With expanding capabilities and complexities of robots, integrating all the safety data from the work cell is required. Industrial safety-rated programmable logic controllers (PLCs) carry this out for robot work cells, to manage and make sense of the data, providing a system view of operations in the work cell. The supervisory safety system collects input data from its many sensors about the status of a person versus a robot within the space, as well as inputs from safety devices such as e-stops, pendants, position sensors and interlock switches. The outputs from the safety PLC supervise control of the robot power circuit, robot servos and other servos in the cell, as well as any other motors, hydraulics or pneumatic devices in the robot cell. All such elements are connected together with the PLC over an industry standard 'safety bus', although the leading suppliers may have their own variations.[51]

Safety technology today also has the potential to provide more granular data via human-machine interfaces. With automated safety diagnostics that already exist, managers may be provided with data on each specific component and circuit, identifying any component causing a problem, rather than having to manually check each part of the safety system. This reduces troubleshooting, maintenance time and overall operating costs, improving mean time to repair (MTTR) and productivity. Ultimately, all data provided is collated and contributes to continuous improvement initiatives by measuring

51 For example, Pilz have a field bus, SafetyBUS p, for decentralised safety systems.

a robot system's faults and failures on a statistical and historical basis. For example, if managers know that a certain safety component historically fails more often than another, the problem can be isolated and corrected.

4.3.1. The market for conventional safety products

Establishing the current size of the market in robotic safety products and services is difficult as data on sales of all types of goods and services falling into this segment is not readily available. Consequently, it is only possible to make an approximate estimate of the value of the market. The size of the safety market must take into account not only the component systems (e.g. light curtains, PLCs, sensors, actuators, interlocks, safety buses, vision systems etc) but also their integration into a complete safety environment. The systems integration value can be as great as, or greater than the physical component value, as for the robotic production system itself. In interviews with industry experts,[52] the proportion of the safety segment is estimated at 10-20% of a total robot installation costs for both products and services. With global robot product unit sales for 2008 of $19 billion (about €15 billion),[53] we estimate the size of the safety element of the current robotics market at approximately €1.4-2.8 billion per year.

4.4. New directions in robot safety – robotics for co-working

As already indicated, robotics is beginning to find application beyond their traditional use in large-scale industrial manufacturing. This is being driven by a combination of market and technological factors. First, the market in traditional industrial robots at best has been growing only slowly for the past decade or more and so new markets are being sought. Second, at the same time technology has been advancing inexorably making new applications possible leading to demand for new applications in new markets. In particular, it is the prospect of human-robot interaction or co-working that offers the robotics sector the potential for significant growth in the coming years (EUROP, 2009).

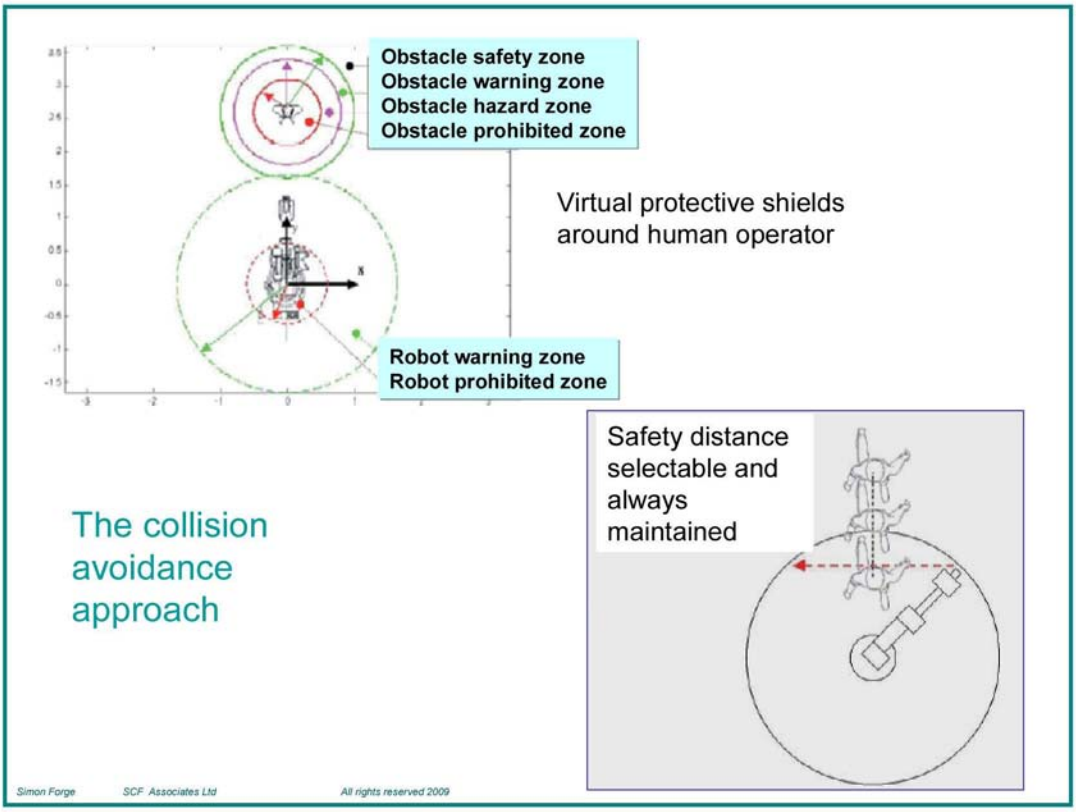
4.4.1. Ensuring safety is key to new applications

The robot applications that are beginning to emerge outside the traditional industrial context require a different approach to safety. Professional and domestic service robots will operate in less structured and controlled environments and most often cannot be physically separated from humans. Indeed, the whole purpose of many of these kinds of robots is that they interact with people in close proximity. Thus, the traditional industrial robot approach to safety of avoiding contact through physical separation is inappropriate for these new applications.

The robotics industry has responded by examining two different approaches to safety for co-working. The first is a development of the traditional collision avoidance approach, although separation is achieved not by physical but by virtual separation by using various kinds of sensors and intelligent algorithms for collision avoidance. The logic is to prevent harm to humans from robots by stopping them from getting too close – so it is still separation but in a slightly different form. Even so, controlling the movement of a robot arm safely in all circumstances is a considerable challenge, e.g. bringing a fast moving arm carrying a heavy weight to a stop instantaneously. What is needed is co-design of the mechanics and control system for safety at all times (Tonietti, Schiavi and Bicchi, 2006). However there are limits on what this approach can achieve, as making a rigid, heavy robot behave gently and safely in any situation is an impractical task. The approach is illustrated in Figure 4.3.

52 Ken Young, Warwick Manufacturing Group.
53 This is taken from the IFR global robot product unit sales for 2008 of $19 billion (about €15 billion).

Figure 4.3: Extensions of traditional robot safety with collision avoidance techniques



Source: SMErobot project Datasheet, Collision Avoidance, 2008.

Despite these improvements in the traditional approach to avoiding collision, it is still inadequate when it comes to the needs of non-traditional uses of robots. This has led to researchers rethinking entirely the rationale to safety, the aim being to assure safety by building an intrinsically safer robot rather than focusing on collision avoidance.[54] The way of thinking borrows from the approach to safety in the automobile sector and in sports (Oberer and Schraf, 2007). In the automobile sector, for instance, it is accepted that collisions will occur and therefore much attention has been devoted to designing cars that cause as little damage as possible when accidents occur. This has inspired research in robotics over the past decade resulting in a new model for human-robot interaction based on lightweight, soft robots which are easier to control and less damaging when involved in a collision.

Interestingly, this direction has opened up further opportunities for the whole robotics industry. The concept of lightweight or 'soft robots' with artificial muscles and 'passive' or in-built safety offers a more appropriate solution for industrial applications where they must assist humans rather than replace them. Established and new robot manufacturers are developing robots based on this new approach (e.g. KUKA).[55] Moreover this evolution could also develop a whole new market in service applications, where humans are served, especially for domestic service robots.

The overall goal of design for interworking, sometimes termed Physical Human-Robot

54 In particular, PHRIENDS, an FP6 project which has examined the problems of robot-human contact and physical structural solutions for safe robots, www.phriends.eu

55 http://www.kuka-robotics.com/en/pressevents/news/NN_060515_Automatica_02.htm

Table 4.1: Comparing the two approaches to safe robots for co-working

Characteristics	Keep using rigid robots	Soft lightweight robots
Design	Design for Accuracy	Design for Safety
Control	Use active control; Control for safety with intrusion detection into hazard zones	Control for Accuracy; Compensation by control
Measures	Increase sensors drastically (force, contact, proximity, etc); Modify controllers for rigid manipulators (stiffness, impedance control)	Mechanical (passive) compliance,[56] through flexibility and softer structures with analogues of muscles, using tension balances.

Interaction (pHRI) is intrinsic safety. This means designing a robot that will be safe for humans no matter what failure, malfunctioning, or misuse may occur. Naturally, perfect safety against all events is not feasible for machines which have to deliver performance in terms of lifting heavy weights and swift motion. The trade- off between safety and performance is the essence of safety in pHRI design. These two approaches are compared in Table 4.1.

Rethinking how robots are designed and function rejects the classic approach of 'design and build' for a specific task. Instead robots would be intrinsically safer since the safety should be guaranteed by their physical structure and not just by external sensors or algorithms that can fail. First is the idea of new mechanical structures for movement and managing the strength and rigidity of moving parts, using concepts of variable stiffness. Associated with this is the materials science of physical structures that will not cause harm to humans.

Solutions based on 'proprioception' can determine the relative position of neighbouring components using special sensors for 'self-awareness'. These enable the robot to react promptly to collisions or crashes and then resume safe operations. But a rapid correction may not be possible if the robot is heavy and solid, as industrial arms traditionally are. The alternative is to ensure that any impacts are gentler, with lightweight and soft robot design. This includes, for example, soft visco-elastic covering on the links in the moving arm, and mechanically decoupling the heavy motor inertia from the link inertia.

In hand with this high-level design approach is the question of what are the main technical developments needed for other components. This includes the need for sensor technology improvement – for speed, orientation, object, optical scene, exteroceptors,[57] etc. Robotics tends to use sensors adapted from industrial automated systems. There is a more general issue here of reliability of all components actuators as well as sensors, as their failure is also a safety hazard – and with it the robot's reaction if hardware or software fails. Similarly, safety also demands ensuring no accidents occur in the event of software defects and failure and robot programming bugs.

What is also needed is more advanced intelligence in the robot, as the presence of humans increases the complexity of the situation in which the robot is operating. A static robot in a protected cell is in a far less complex situation than a robot operating in an open environment, especially if it is also mobile. The ability to process and interpret large volumes of information requires sophisticated, robust algorithms for detecting objects; it is the subject of much current

56 The passive safety compliance approach has been explored by various research projects, not just in the EU, as with PHRIENDS, but also is also being explored for instance in Korea University, Seoul, Korea as the Safe Joint Mechanism (SJM).

57 Exteroceptors are sensors that measure the positional or force-type interaction of the robot with its environment and can be classified according to their range as contact sensors, proximity, or far sensors.

research in the EU. Thus in this more complex situation, different circumstances will dictate what the response of a robot should be if a fault is detected. Simply shutting down may not be the appropriate response with fail-safe concepts for life critical systems.[58] This raises the question of laws or protocols for ways of working, i.e. the rules a robot operates under.

Moreover, further research is needed to bring technical advances in sensor processing software for, e.g. scene analysis with image processing. Much of the advanced software in this realm is bespoke and there are no general products. The research community is developing algorithms and so libraries of these are beginning to appear as open source software, e.g. for face detection image processing. Successful proprietary software with implementation support and updates is not yet available. On the other hand, some low-level-intelligence algorithms are available, such as stereovision algorithms (i.e. calculating 3D information from two camera images without image recognition processing of the 3D information) or self-check-routines.

There is also the question of what is sometimes termed robot middleware - a layer of communication between different robot sub-system components, defining data structures, message formats and message priority, a form of intelligent information bus. However industry standards for robot middleware are still far away[59] (e.g. there is even no agreed definition of what robot middleware is).

4.4.2. Understanding injuries to prevent them

If closer human-robot cooperation means that there is a higher risk of injury to humans, then the industry has recognised the need to better understand how injuries occur so that their incidence can be minimised and so that their effect can be minimised. This has resulted for the first time in substantiated quantitative analysis of the dangers of the robot, using indices of risk. Here the robot industry is learning from the automobile industry about vehicle safety using crash tests, experimenting with dummies and testing, e.g. for head injury due to robot impacts (Oberer and Shaft, 2007; Haddadin, Albu-Schäffer, Frommberger, Rossmann and Hirzinger, 2009a, 2009b). These studies involve analysis of biomechanical and forensic injury criteria using collision simulations as well as real crash tests involving dummies and various robot arms with payloads, ranging from 3 to 500 kg to build robot risk criteria.

Thus the robotics industry is learning from those industries and sectors where useful, relevant research is done, those where safety has been taken really seriously, such as in car design and also in sports. This is leading to a deeper understanding of the severity of potential human injuries, which in turn is yielding design recommendations for intrinsically safer robot systems. If a robot is suitably designed, it is possible to reduce the severity of physical impacts and also the force behind the impact itself, so that any collisions are less damaging. Analysis shows that a robot is not as intrinsically dangerous as a car.[60] Nevertheless, it has to be recognized that the incidence of injury and fatality are not the main problem – what has to be presented to the public is the assurance of not being hurt at all.

4.4.3. The robot safety industry itself is changing

For co-working, users want robots with the assurance of no injury in robot-human collisions. More work is still to done on the technologies of human-robot interaction and detection of proximity, but there is a clear direction emerging within the sector of the development of soft

58 Interview, Theo Jacobs, Fraunhofer Institute for Manufacturing Engineering and Automation (IPA).

59 One research project currently working in this domain is RoSta, with partners including Fraunhofer IPA (http://www.robot-standards.eu/index.php?id=19).

60 Interview with Antonio Bicchi, University of Pisa.

robots, not just in material but also in movement.[61] This requires a passively compliant trunk, a soft manipulator and passively moveable base – that is the base and trunk will move even with a light touch out of the way of a human.

This implies progressive changes in what is the safety industry for robotics. The suppliers of today's robotics safety systems and components are generally concerned with the wider subject of industrial safety, supplying systems that surround a separated robot as just one segment of a far wider market. Thus although industrial robotics currently uses the safety industry's components and sensors, such new directions in robots themselves are outside their core interest. On the other hand, the actual robot manufacturers (e.g. KUKA and ABB in Europe and Motoman in Japan) are very active, for instance in designing new models as well as in the standards bodies such as ISO.

It is also important to realise that a part of this new direction will still be based on standards and regulation, which the industry needs as both guidelines and a limit to liabilities. But regulations and standards that become obsolete will be an obstacle, and so must be revised continuously. Thus certain technology research projects much emphasis is put on bringing any results related to safety measures to the standard bodies' attention (e.g. as in the EU PHRIENDS project).

4.5. The overall market potential for safe robotics

Forecasting the market potential for 'safe robotics' with any accuracy is difficult because there are currently too many unknowns. For instance, how safe can robots become? Will soft robots be affordable and easily implementable and so help to open up a new market in SMEs? Will personal domestic robots be seen as acceptable in the home? In this section we consider these and other factors to evaluate the likely development of the market.

4.5.1. Is a point of weak discontinuity in the robotics market at hand?

Our analysis of market trends, research and interviews with industry experts indicates the possibility of point of 'weak discontinuity' for the robotics industry in the next five years. The development of safer, softer and more lightweight robots for co-working is significant and progressing such that it could have far-reaching impacts. It could act as a point of convergence for the various types of robot, from the dominant industrial robot to the developments in the still-emerging service type and humanoid robots, as well as mobile robots. Thus all other types of robot might be influenced by this new category.

If safety in robot can be assured, researchers and industry experts in the robotics sector believe that it will provide the platform for design of safe domestic service robots, for use in the home and hospital, especially for care of the aged and infirm.[62] This could result in all types of robot converging towards a new category of co-working safe robots, as illustrated in Figure 4.4.

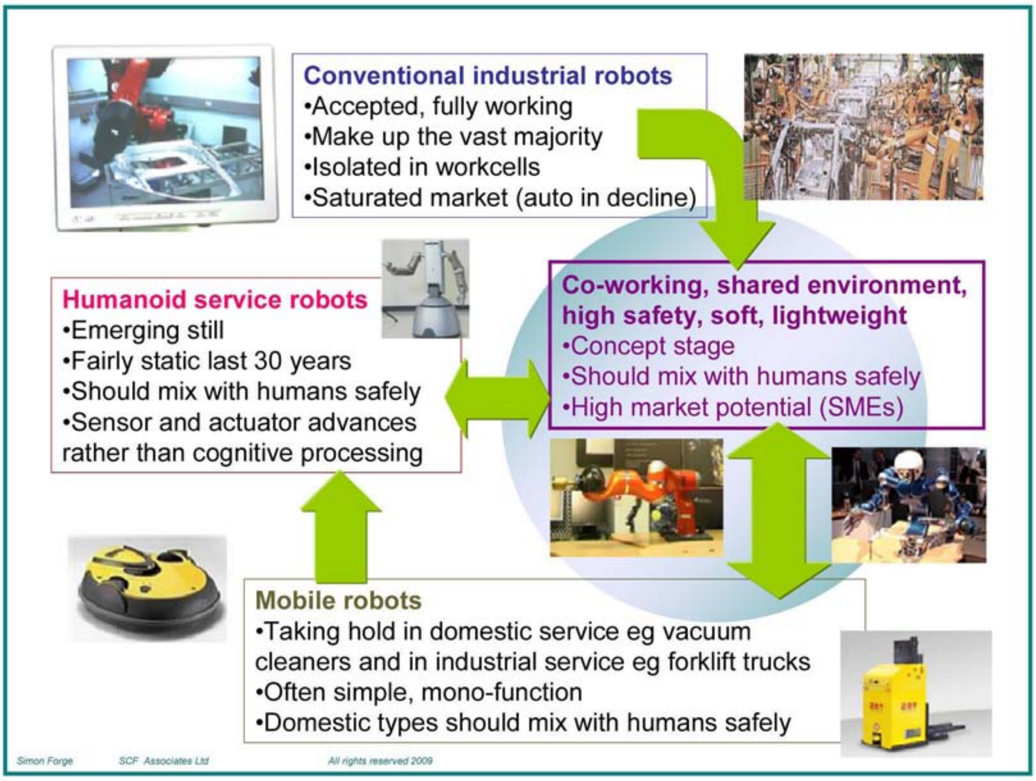
The impacts of this trend on the supply side, in terms of the industry's value chain, are manifold:

- With safety built into the robot, the early part of the value chain would be modified:
  - Increased R&D on injuries and design strategies generally,
  - Investments in development of new types of actuators and arms, perhaps based on

61 Examples include Shadow (http://www.shadowrobot.com/), Barrett Technology (http://www.barrett.com/robot/index.htm), and KUKA (http://www.kuka-robotics.com/en/pressevents/news/NN_060515_Automatica_02.htm).

62 E.g. researchers at the Fraunhofer Institute (http://www.care-o-bot.de/english/index.php), and the Institute of Automation, University of Bremen (http://www.iat.uni-bremen.de/sixcms/detail.php?id=95).

Figure 4.4: The convergence of robot types



tensioning for arm 'muscles' that give variable stiffness and so soft yielding characteristics, plus more sophisticated vision, audio and communications sensing,

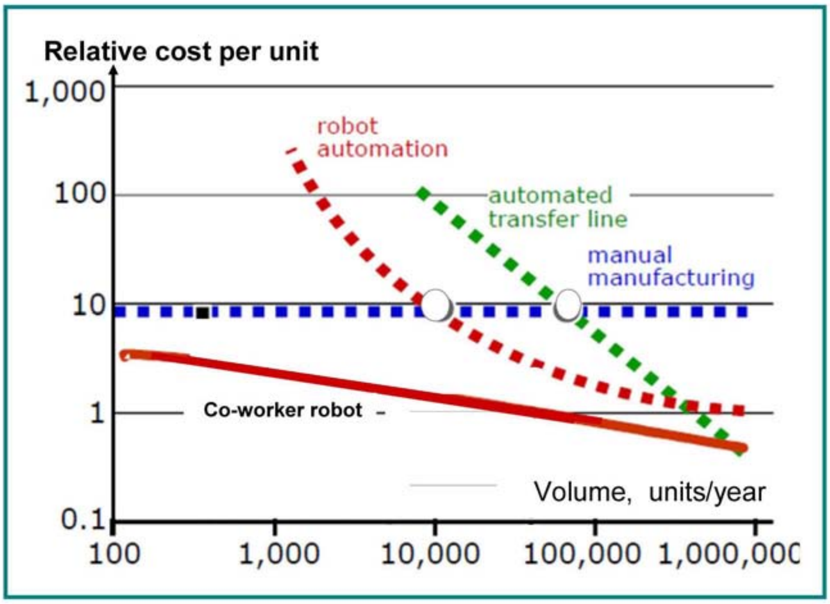
– Research investment on materials for lighter weight, non-injurious moving assemblies,
– Research into detection of light touch resistance,
– New software investments for different control strategies,
– New production assembly techniques, for higher volume at low cost (robotic),
– A different range of components, lighter with different operating principles (e.g. opposing tensions rather than heavy torque motors).

- As safety is being built in as a passive mechanism, investments in external safety devices and mechanisms would be lower in this new segment compared to the traditional separated industrial robot in its safety cage with safeguarding systems. System integration costs for this external equipment would also be significantly reduced.

- Similarly, with safety embedded within the robot, setting up and using such robots would be simpler and easier, and so the system integration component would be different to a traditional implementation for a large production line. Set-up with other machines in a work cell might even be eliminated, as co-worker robots would continually adapt on human command, perhaps that of an untrained operative. In these circumstances, the robot system integration industry would be modified but not necessarily reduced. In fact, as robot take-up proceeds, the S/I sector is more likely to flourish and create new employment, through three drivers:[63]

63 Interviews with Geoff Pegman (RU Robots), Ulf-Goran Norefors (ABB Robotics).

Figure 4.5: Positioning the co-worker robot in terms of industrial production volumes



Source: Norberto Pires, J. et al 2008, Universidade de Coimbra, Italy.

- More users (both large companies and SMEs) and so more customers with start-up training and introduction demands.
- Strong relationships for S/Is with both the original robot manufacturers (OEMs) by acting as their key channel to the market and also the application providers for software and tools (ISVs and ITVs)[64] for whom the S/I is both an on-site partner and sales channel.
- Success in this new segment will be based on an eco-system of support, especially for SMEs, as shown in the previous chapter. This comprises end-user SME interest groups, robot and technology suppliers, S/Is and VARs. It exploits a similar structure to that which has evolved in the computer software and hardware industry over the last thirty years. Overall, the supply side stimulus of a new market for soft robots is a key attraction for the European robotics industry

4.5.2. The demand side characteristics of a potential new market

The co-worker robot market segment is likely to be characterised by limited production volume with high flexibility for lower cost of changes to the robot's programming, because tasks will change far more frequently than in mass production.[65] It is also characterised by a lower cost model, in order to be attractive to new user segments as well as the current large industrial users. This is illustrated in Figure 4.5, which shows how costs vary with production volumes for different approaches to industrial production. It indicates that for practically all volumes, the relative cost per unit of production is lower for a co-worker robot than either manual production, traditional robots or automated production lines. Moreover, co-working robots would be cost effective at relatively small levels of production. In other words, take up is likely to new users in SMEs where cost is traditionally a major barrier.

64 ISV, independent software provider and ITV, independent tools provider, VAR value added reseller.

65 Interviews with Antonio Bicchi (University of Pisa), Martin Hägele (Fraunhofer Institute for Manufacturing Engineering and Automation).

Thus, although initial applications for co-working robots in SMEs are likely to be niches such as in manufacturing, in metal and plastics forming and processing, etc, such robots could migrate across many sectors. Moving into all sizes of enterprise for more conventional applications can be expected, such as electronics assembly, as well as introduction into food processing, biotechnology, clothes and textiles. These are sectors where the high force, hard surface characteristics of the conventional industrial robot could be replaced by low force delicate actions for what might be termed 'soft products' demanding precise small forces but in a non-repetitive mode of work.

Beyond manufacturing, there is considerable scope for safe co-working robots in professional services such as industrial cleaning, surveillance and repair (e.g. underwater co-workers for divers, etc) but also in human contact industries such as medical applications (from intense care for the elderly in the home to operating theatre attendants for surgery). This market is in its early stages of development with simple lawn mowing and vacuum cleaning robots already in the market.

If safety can be assured, then the market for co-working robots in the domestic market is potentially large. Nevertheless, it is likely to be some time before functionality, price, and market confidence come together to build a domestic service market, researchers and industry experts suggesting this development is not likely until after 2020 or 2025 at the earliest.[66]

The market potential for safe robotics in the EU and forecasts from a geographical perspective outside the EU (i.e. export potential) are thus of key interest for future industrial policy. It is therefore useful to try to understand the pace of market development for co-working robots. The catalyst for this new market would be safety combined with low robotics skills in the end-user enterprise. In other words, compared with most current robots, far more would be built into the robot itself for safety for co-working with humans and for ease of reprogramming to match the end-user environment. Research institutes are developing robots with these kinds of characteristics but to commercialise such robots, and for the full market potential to be reached, is likely to take at least 10 years. It is conceivable that a limited market, initially in the smaller enterprise for manufacturing, could be established after 2015, which might then be taken further into other sectors, i.e. building up gradually, over another five years, with a full cross-sector achieved only after 2020.

However, this is not the whole story. First, the export potential of co-working robots, while clear, is difficult to estimate. It is evident that the first export markets could be similar manufacturing markets in large companies and SMEs in North America and some parts of Asia. Second, with establishment of an industrial market for co-working may come the experience and technologies for seeding the co-working professional services market globally. It is possible that a global domestic service market may later flourish, perhaps with earlier export sales being to Asia, especially Japan.

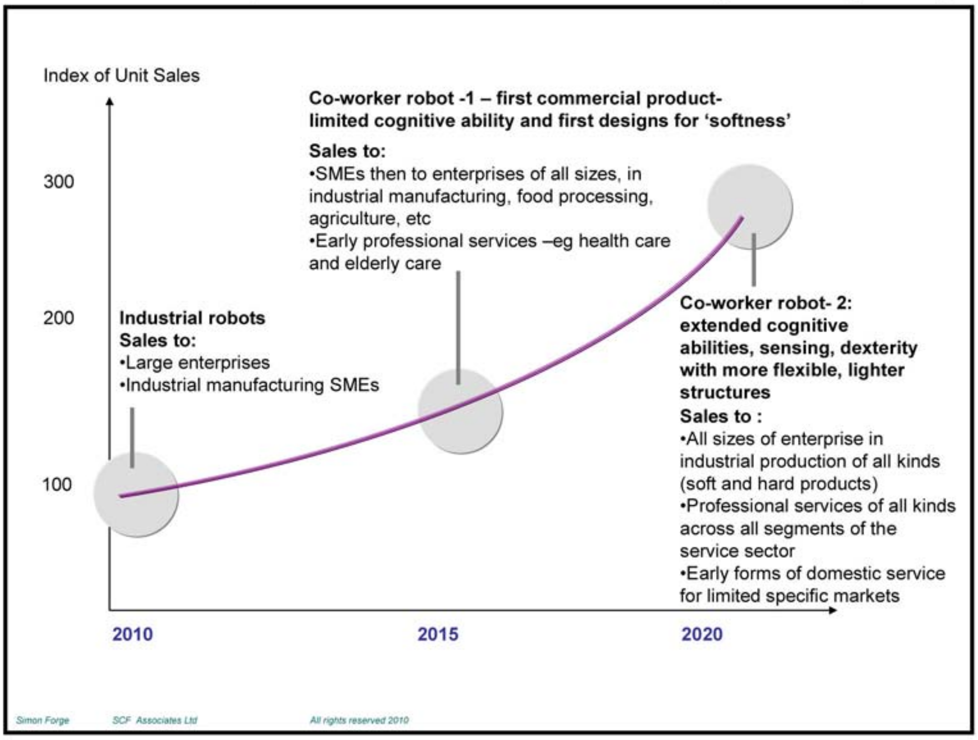
The development of these three markets could take place in three phases:

- an early phase of trial and experimenting by industrial end-users (of all sizes of enterprise),
- then a pure industrial manufacturing co-worker market, spreading globally,
- and finally a mixed SME/professional service robot market (with domestic services coming much later).

This is envisaged in terms of product projections in Figure 4.6.

66 Interview with Birgit Graf, (Fraunhofer Institute for Manufacturing Engineering and Automation).

Figure 4.6: How the market potential of the co-worker robot segment may emerge



4.5.3. In summary

A new approach to safety is required for applications that demand interaction between robots and people. By definition, a co-working robot cannot be separated from humans in a protective work cell. The new approach means embedding safety within the robot itself so that if collisions do occur they will be less damaging. By following the approach in the automobile sector to road and vehicle safety, research is leading to development of lighter, softer and safer robots.

The development is opening up the possibility of much wider dissemination of robots in new environments – in SMEs and in new applications in large firms. It also brings forward the prospect of service robots in professional and eventually domestic environments.

5. Supporting the opportunities in the EU robotics sector

5.1. Introduction

This final chapter addresses how, in terms of policy, the competitiveness of the EU industry in the robotics sector could be better supported. This chapter comprises three sections. First, industrial policies concerning robotics around the world are explored, i.e. how various countries have built up their robotics industry and what their policy and strategy is likely to be in the future. Second, the competitive position of the EU as compared with other countries and regions is analysed. This is measured on the key parameters of industry strength and capability to compete in the future. Finally, the policy issues, goals and actions to take advantage of the potential opportunities are elucidated.

5.2. Industrial policies in robotics outside the EU

5.2.1. International comparisons of industrial strategy in robotics

Comparing the position of the EU in robotics with the national strategies elsewhere is a key component of industrial policy. The Chinese, Korean and Taiwanese robot industries are all interested in traditional manufacturing robotics as well novel concepts beyond their mainstream strategy, but to differing degrees. For example, high-end personal robots, especially domestic humanoid robots, are the focus of much university and industrial research in Japan, Taiwan, Korea and China. Although general-purpose humanoid robots capable of helping with everyday domestic but complex tasks remain a distant goal, several Japanese companies (e.g. Honda, Sony, Kawada, and Toyota) and a handful of Korean and Chinese suppliers have research prototypes and continuing programmes.

Japan: The government, through its policies of building high-tech domestic industries, gives long-term support by coordinating the major players through industrial programmes. Selective protection and encouragement have been, and will be, given to key industries, of which robotics is defined as one. Instruments include access to low-cost capital, tax exemptions, tariff barriers, and restriction of inward foreign investment for control of strategic industries until a global parity is reached (Noland and Pack, 2003). Publicly-funded support for R&D through the phase of commercialisation had a major impact on the electronics industry from 1970 to 1985 and this strategy is likely to be repeated in chosen high

Table 5.1: How Japan rated itself globally in 2001 in robotics

Robotics Applications Sector	Japan	USA	EU
Manufacturing	XXX	XX	XX
Construction	XXX	X	X
Welfare/care	XX	XX	XX
Nuclear power	XX	XXX	XX
Bio-industry	X	XX	XX
Service applications	XX	XX	XX
Medical	X	XX	X

*Key: **X**: below global leadership; **XX** at global parity with others; **XXX**: highly globally competitive (leader probably).*

Source: Japan Robot Association, 2001.

technology sectors. There is constant surveillance of the competitive position. For instance, the Japan Robot Association's 2001 assessment of its capability compared to other regions is shown in Table 5.1.

It is interesting to understand on what basis this assessment of international competitiveness was based. Four criteria were used:

- Ability to create unique products, subsequently copied by other nations,
- Ability to create an export market for the product,
- Domestic market larger than those of competitor countries (often seen as a key factor in Asia),
- Ability to create markets – i.e. go from prototype to demand-led commercial products.

Japan's strategy until recently has been to concentrate on manufacturing to support its car industry. By 2001, it had already acknowledged that other countries were leaders in non-manufacturing fields of robotics and since then, it has tried to catch up. Its interest in the wider range of robotic applications, however, as seen in the 1970s and 1980s, waned as the domestic markets failed to appear outside manufacturing.

Thus although Japan may appear to be at a globally competitive level in various types of industrial manufacturing robots, its current efforts for the future seem geared towards an all-function humanoid-type robot, rather than one with only dedicated functions. Hence Japan is investing some $350 million (€280m) over 2008-2018 in humanoid robotics, service robots and intelligent environments (National Academy of Engineering, 2007; and Computing Community Consortium, 2009). This strategy is likely to be expensive, with uncertain results and products that may be late to market. Early models for the domestic market have apparently not sold well – there have been several high-profile attempts (e.g. Sony's SDR-4X) but so far they have typically been too expensive with limited functionality and questions remain about their acceptance. At the same time, all the mainstream suppliers are hoping for a revival of fortunes in manufacturing, especially in the auto industry, which would allow them to remain with their known customers, supply chains and product lines. The main Japanese industrial robot suppliers are also interested in lighter robots (e.g. Motoman and Fanuc, especially for the food industry). It is unclear whether the industry's exports worldwide in any such new robotics segment would match today's market situation, where leaders from Japan (e.g. Fanuc, Denso, Kawasaki and Motoman) are already significant or dominant exporters to the USA, China and the EU. Instead, new Japanese players might enter, from electronics, games players, or car manufacturers, or perhaps the current players would expand.

China: China is a relative newcomer in the robotics sector. It is interested in conventional industrial robots and its output of industrial robots was valued at over €400 million in 2007.[67] It is a major and expanding user of heavy industrial robots, for its car industry and in shipbuilding, using large Korean robots and also those from many others including ABB and Kuka. The local market for industrial robotics is so important that, in 2006, ABB moved the world offices for its robotics division to Beijing. China is now entering the next phase, in which it will expand its educational spending on graduate and post-graduate education and R&D for robotics engineering. With this intellectual capital, it expects to become a competitor in more sophisticated robot segments, in both design and manufacturing, over the next two decades.

Overall policy is set by political conditions. China needs to grow its economy. But like its neighbours Japan and Korea, it intends to maintain control over crucial industries. Thus

67 From China Industrial Robots Report. The National Bureau of Statistics of China puts the 2007 industrial robot output value at RMB 4.12 billion, a growth of 460% over 2003, at: PR-inside.com.

China's overall industrial policy is characterized by three main thrusts:

- creation of an export-led and foreign investment-led manufacturing sector, following the footsteps of Germany, Japan and Korea.
- an emphasis on fostering the growth of industries such as high-technology products that add maximum value to the Chinese economy.
- creation of enough jobs to reliably employ the massive Chinese workforce.

To do this, it must attract foreign capital and also foreign technology. Hence industrial policy follows much the same route as it took for electronics, PCs (e.g. Lenovo) and telecommunications (e.g. ZTE and Huawei) where it pushed for an apparently laissez-faire, opportunistic market combined with tightly centralised control of key actions through:

- Monopsonistic power – just as the Japanese government used to do in the 1970s when their R&D-intensive drive began with microelectronics, numerically controlled machine tools and aircraft, the Chinese government intervenes on behalf of manufacturers as the single purchaser of any desired technology in order to get a better deal (Noland and Pack, 2003).
- Restricting the entry of high technology vendors to joint ventures with a Chinese technology partner.
- Ensuring that technology transfer is part of any joint venture, often through industrial offset contracts.[68]
- Climbing up the value chain by educating knowledge-based workers, so that China can move away from low-end, labour-intensive manufacturing and being just one part of a global production chain or network.

Just as it is in Korea (and in most centrally-planned economies), Chinese industrial policy is activated through multi-year plans. The first ICT multi-year plan was the '863' programme of 1986 which resulted in the development of a Chinese robotics industry. Industrial and humanoid robots have been exhibited ever since (e.g. 'Blue Superman' from Harbin Industrial University in 2002). The 863 programme remains part of the 11th 5-year plan endorsed by Chinese leaders in 2006. At the same time, a 15-Year Medium-to-Long-Term Science and Technology Plan (MLP) was put in place.[69] This laid out an innovation roadmap for re-orienting the economy away from a model based on low-end manufacturing driven by cheap labour, with an over-reliance on fossil fuels, extensive consumption of natural resources, and an apparent insensitivity to the environmental implications. The MLP focuses explicitly on enhancing China's capacity for independent innovation (*zizhu chuangxin*).

The goal is to ensure that increasingly all intellectual capital and know-how utilised across the Chinese economy derives from indigenous sources rather than know-how and equipment simply imported from abroad. The Chinese emphasis on independent innovation does not mean a return to the self-reliance policies of the Cultural Revolution (*zili gengsheng*). China intends to remain fully engaged with the world, as globalisation has proven to be a major driver for its economy, bringing increased knowledge acquisition, investment, and trade. Globalisation has engendered the massive explosion in foreign investment from around the world - China has been in the top five recipients of FDI annually for the last decade.

68 A recent example is in high speed trains, where a consortium led by Kawasaki has so efficiently transferred its technology, that China's CSR Quingdao Sifang now builds two of its own design of bullet trains per week (Dickie, 2010).

69 Hearing of the US-China Economic and Security Review Commission, USCC, on China's Industrial Policy and Its Impacts, March 24, 2009 from Denis Fred Simon, School of International Affairs, Penn State University.

China has also set up the Torch Programme, a complementary project for commercialisation of R&D. It ensures that research results get translated into new usable and commercially-viable products and services. Torch operates many of China's technology incubators, to bring to market innovations by young start-up companies, which need help securing enough capital and/or talent. It also manages the fifty national science and technology industrial parks, under the aegis of China's State Council. These centrally-directed programmes have had highly mixed success, with some significant failures.

However, one child of these initiatives, the Siasun Robot and Automation Company in Shenyang is a key success (and affiliated to the Chinese Academy of Sciences). The founder and CEO is now Deputy Director of China's National Engineering Research Centre on Robotics. As did many leading Chinese technologists, this CEO spent the early 1990s studying robotics and automation in the West, in Germany, returning to China in 1993. Siasun has a 90% share of the domestic robot market, with sales of 880 million Yuan in 2008 (about €97 million). It has 30% of the industrial robot market in China. The company received funds and support from the 863 Programme, under the Ministry of Science and Technology, for establishing an 'intelligent robot industrialisation base'. Siasun robots and automation equipment are used in the auto industry, rail transit, the energy sector, logistics and storage and clean room automation. It seems positioned to continue its steady, albeit gradual, march to becoming a global player in robotics.

Korea: The government has designated robotics as one of ten key technological areas which will drive its economy anf will thus receive investment in R&D to bring products to market. This sector's aim in Korea is to introduce common household robots by 2020. As always, South Korea is basing its strategy on a managed economy policy, with the following characteristics:

- Long-term planning –either 5 or 10 year economic plans. The current 21st Century Frontier Programme will spend $1 billion (€0.8 billion) on robotics research and education, at the rate of $100 million (€80m) per year over the period 2002-2012.
- Government orchestration of, with and by the Chaebol –the major conglomerates such as Hyundai and Samsung.
- High tariff protection with a view to building a domestic market for its export products. Korea will then slowly open up to foreign competition, in order to improve domestic products.
- Creation of export markets with cost competition and long-term financing of export efforts through various tax and subsidy incentive programmes.

Korea is now investing in university research on safe robot arms with non-linear elements and has laboratory models under development.[70] Korea's place in world markets for the heavy car industry and heavy engineering robots has been established over the past decade, especially by Hyundai that also manufactures robots for car production, and also by the Daewoo shipbuilding conglomerate, which has progressed into welding and large crane robots for export sales. A new force in this market could be collaboration between Korea, China and Japan, combining their studies and industrial research in robotics.[71]

Taiwan: Here also, policy clearly aims to support robotics, which has fairly recently been defined as a strategic target sector. This push is as strong as Korea's managed economy. Taiwan's policy for robotics is focussed on building an industry by importing from overseas fundamental technologies and IPR through encouraging partnerships. Interestingly, Taiwan is targeting software as much as whole robots. For instance, it is promoting partnerships with US robotics

70 For example, work in the Department of Mechanical Engineering, Korea University, Seoul, Korea.
71 Interview with Geoff Pegman, RU Robots.

Table 5.2: Example of support actions by the Taiwanese government

Tax Incentives • Investment tax credit for shareholders, or 5-year tax exemption for emerging, important, and strategic industries • Personnel training expenditures (business income tax credit based on 35% of all training expenditures in the same year) • R&D expenditures (business income tax credit based on 35% of all R&D expenditure in the same year) • Accelerated depreciation of facilities (maximum depreciation period: 2 years) • Tax credit for the purchase of facilities and technology investment • Tax-exemption for imported components • Tax incentives for technology transfers or cooperation • Incentives for the establishment of operations headquarters	**R&D Subsidies - a series of defined programmes** • Industrial Technology Development Programme • Small Business Innovation Research Programme • Industrial Technology Development Alliance Programme • Strategic Service-oriented Industry R&D Programme • Information Technology Applications Programme • Industrial Technology Innovation Centre Programme for Local Enterprises • Industrial Technology Innovation Centre Programme for Foreign Enterprises • Leading Innovative Product Development Programme • Enterprise R&D Alliance Programme • Enterprise Operation Headquarters Service
Low-Interest Loans • Industrial R& D Loans • Low-interest loans for mid- and long-term capital • Project loans for small and medium enterprises • Bank draft and loan preferences for development fund • Low-interest loans for science parks	**Personnel Training** • International expert recruitment • R&D alternative service - R& D substitute service programme office • Military training service application

Source: Ministry of Economic Affairs, 2008.

companies that focus on the software (Ministry of Economic Affairs, 2008), especially with those that have affiliates in Taiwan (e.g. Cognex, which makes machine vision systems for the semiconductor industry, and is in partnership with AUO for robot vision systems) and with robot suppliers (e.g. between robot supplier Korntech of Korea and FarGlory of Taiwan). Thus the government is orchestrating a policy to build a whole new high technology sector from scratch.

The goal is global market entry, following a robotics roadmap:

- First, the early establishment of capabilities over 2005-2008,
- Then, triple-fold industry expansion is anticipated from 2009-2013,
- Finally, the establishment of a global intelligent robot manufacturing centre is forecast for 2014-2020. This will target niche markets, including 'lifestyle' or domestic service and medical applications.

Taiwan aims to achieve this by attracting 'intelligent' robots expertise through technology transfer from overseas partners. It aims to provide support for training, tax relief, R&D support plus low interest loans for mid-term and long-term capitalisation for moving from a prototype robot to full commercial production, as shown in Table 5.2.

The ingredients for success in Taiwan range from small business innovation support to longer-term capital being made available for moving into commercial production. Once innovation has succeeded in producing working prototypes, there will be ongoing support in various forms including tax breaks on capital purchases, with stimulation of clustering, for instance through the establishment of science parks and active co-ordination.

USA: There is a large market in the manufacturing sector, but less ability to service it from indigenous robot makers, even though the first major robot supplier, Unimation from the 1950s, was a precursor of today's industry. As ever, US industrial policy contrasts strongly with Asia and the EU. The US robotics policy has much in common with its other industrial policies (Computing Community Consortium, 2009). It quite deliberately relies on the large-scale spend on military service robots to percolate out into civilian applications. Hence, the federal state does effectively support the private sector in its early R&D and commercialisation stages – the internet could be said to be an example of this.

Industrial policy as an explicit entity is a minefield politically in the USA so that the approach is largely via government grants for R&D (e.g. from the National Science Foundation) and military contracts. Overall, the US strategy, while dispersed across several funding agencies and not explicit, is quite well prepared. As a result, its policy, research and output are concentrated mostly on a range of service robots, often mobile.

A key instance of this transfer mechanism in robotics is iRobot, known for its Roomba vacuum-cleaning robot and similar domestic appliances. The origins of iRobot are in military battlefield and hazardous situation robots, which have expanded today into aerial and subsea robots, sometimes via acquisitions. iRobot started as a spin-off from MIT, moved into military and then into the home service domestic market. This development model also means the vacuum cleaner product itself can be made outside the USA, in any low cost labour economy such as China.

Perhaps due to this type of policy and support, the US robotics industry is more focussed on applications outside industrial manufacture for robots in, for example, military and medical fields (Computing Community Consortium, 2009). Only about 10% of industrial-type robots come from the USA whereas the vast majority are from Asia and the EU. Suppliers such as Fanuc, Motoman, ABB, and Hyundai of Korea all have local USA affiliates selling robots and offering systems integration through S/I channels, with a strong VAR structure. There is a lively local eco-system for the industrial manufacturing sector with resellers and subsystem builders for vertical segments in manufacturing and medical, such as Peak Robotics and Applied Robotics, which may also act as dealers for the larger names.

However, again, the main robotics development effort in the USA is military, where it leads globally, owing to its defence spending focused on unmanned vehicles and other types of military applications. Also, the USA's space programme is expected to depend on co-operating teams of robots designed for in-space activities, with its new policy and programme of unmanned missions. This NASA/GM collaboration is a first step towards this. It will be interesting to see whether current defence and space applications will seed the future new areas, such as co-operating robots for space, and whether these then progress into spin-offs as service robots, for professional and domestic purposes and also perhaps for SMEs.

5.3. The competitive position of the EU in the global market

5.3.1. The state of the global industrial robotics industry and potential new markets

In Chapter 2, we emphasised the fact that the market for conventional industrial robotics for large-scale automated manufacturing is becoming saturated, as there is limited room for future growth. This finding has been confirmed by other studies (Ministry of Economic Affairs, 2008). Moreover, with the financial crisis, world robot sales to the manufacturing industry have shrunk by almost 30% (Brumson, 2010). This implies that the safety market arising from the manufacture of conventional industrial robots, aimed at larger enterprise implementations, is also likely to remain static, or even shrink. The demand for current types of large industrial robots over the next five years is likely to stagnate, as demand overall in the global economy is only recovering slowly from the financial crisis of 2008/09.

Customer demand in the OECD countries for mass-produced consumer goods may continue to be weak for some years. These goods are produced by the types of industry which industrial robotics typically serve (car and trucks, white goods, electronics, etc.). Whether demand in the developing world, the source of much consumer manufacturing and components, will compensate is unclear, as there is a causal chain here. Demand by consumers in OECD countries drives production levels in producer countries;

their demand for robots is controlled by the OECD consumer demand, just as it is within the OECD community.

Potential new market directions for the EU robotics industry include:

- Applications in more industry sectors – food processing, energy, transport and logistics, health care, security, consumer, etc,
- New applications in segments within the above sectors – e.g. in medical for healthcare and also in other professional services such as subsea robots in energy or cleaning and de-icing aircraft in transport.

A focus on this opportunity, also highlighted in EU FP6 and FP7 research, presents a new paradigm of affordable and flexible robot automation technology (e.g. 'plug and play'). This technology would meet the requirements of many sectors, and could be the enabler for a step change in demand for robotics. At the same time, such robots could have a significant impact on productivity in the EU economy when deployed in European industries.

5.3.2. The state of the EU's robotics sector

Despite the recent economic shocks and demand downturn, the robotics industry in the EU is still healthy. EU competency in robotics research is high with world leading research in many research institutes. The EU already has a strong technical and commercial competence in the robotics sector in certain Member States – notably, France, Germany, Italy and Sweden – with world-level skills built up for the large enterprise users, which could be refocused on new robot markets.

5.3.3. The position of the EU in robotics from the value chain analysis

To gauge the EU's position in the global robotics market, the complete production cycle is examined in this report following the general value chain analysis (see Chapter 2). EU competitiveness for each major link in the value chain is shown in Table 2.8, which illustrates the relative strength of EU companies in the value chain. It points clearly to future opportunities for success for the EU industry in a future evolution of the current product lines.

Currently, the general strategic behaviour of the major EU players is to seek new segments and expand out of the conventional industrial robots market, while maintaining market shares in that segment. Thus all are interested in new segments such as lightweight robotics with collision avoidance and minimisation of dangers to produce co-working types. Both ABB and Kuka Roboter have developments and new models appearing for this market, many as a result of the work done in various EU research projects.[72] These are lightweight robots which use the new forms of 'muscle' with counteracting forces. Comau is also a participant in certain projects, as are several other smaller European suppliers, plus certain key government agencies able to produce and commission these robots, such as the German Aerospace Center, DLR.

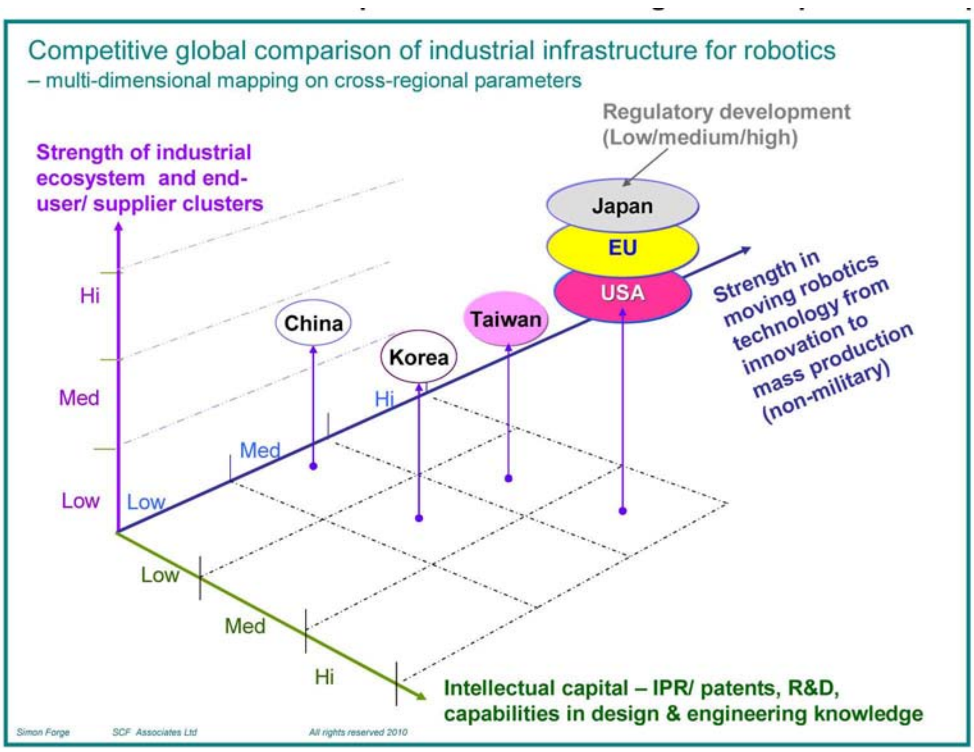
5.3.4. Comparative assessment of EU global competitiveness

Considering all this information, it is possible to make an assessment of the competitive position of the EU robotics industry, commercially, technically and strategically. This is measured by a set of specific industrial parameters. These key competitive indicators are analysed both at the level of industrial infrastructure and regionally. First, the industrial infrastructure needs the following attributes in order to be competitive:

- Intellectual capital: IPR, R&D efforts and investments, including patents produced.

72 E.g., the SME Worker's Third Hand, SMErobot Datasheet, http://www.smerobot.org/download/datasheets/automatica/SMErobot_DataSheet_WorkersThirdHand.pdf

Figure 5.1: Industrial infrastructure parameters for future global competition compared



- Strength and experience in moving robotics technologies from innovation to (mass) production for a commercial market.
- Strength of industrial ecosystems and end-user/ supplier clusters.
- Regulatory development (important for safety matters).

Figure 5.1 summarises the position of the EU compared to other global players.

The assessment is based on an analysis of information gathered during the course of the study, through desk research and interviews with industry experts.

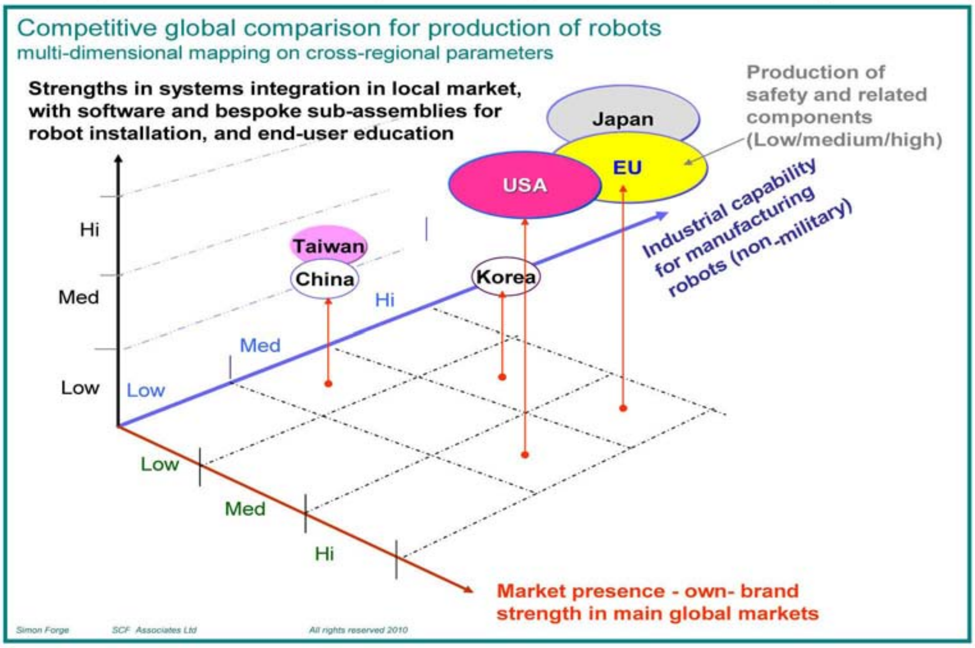
Second, Figure 5.2 compares the EU with other regions based on the means of production and commercial operations with the key competitive indicators being:

- Strengths in systems integration in the EU market, with software and bespoke sub-assemblies for robot installation, and SME education,
- Global branding and market presence,
- Industrial capability for manufacturing robots on a commercial scale,
- The capabilities/competences in manufacturing major safety-related components.

For each parameter, the diagram identifies current strengths and weaknesses of each region and thus tends to indicate the strategic behaviour of players in the market with technologies, marketing, alliances and target application segments. Overall, the EU industrial infrastructure seems comparable with other regions where advanced robotics is concerned.

As regards production and marketing status, again the EU has similar capability to other leading regions, and is quite able to compete globally. In the key area of systems integration, which acts as a channel to market, European suppliers are well organised and give support to S/Is and other channel partners. The S/Is are also quite capable of responding to the demands for vertical sector

Figure 5.2: Comparison of industrial production parameters for future global competition



expertise, e.g. techniques for handling delicate food for packaging under health regulations.

Taking into account all the available research, the EU's global market positioning is summarised in Table 5.3, exposing the strengths and weaknesses of the EU.

In conclusion, Europe's future role lies in exporting, if it can build on the domestic market, and so operate at the level of the major players – Japan, the USA and Korea, while leading China in technology and production.

The EU has yielded leadership in components and low-end assembly type manufacture to Asian suppliers, especially Japanese producers such as Denso and a wave of lesser-known Chinese and Taiwanese manufacturers.

However, the EU is better placed in the robotics sector than in some other high technology sectors (such as microprocessors, displays, memory, etc) because of the strength of its supplier eco-systems in building an infrastructure for manufacture. It has several clusters of expertise in robot systems integration and manufacturing and is also well placed for robotics technology innovation and design.

On the demand side, today's markets for robots are compared with likely future ones in Table 5.4.

Considering potential for longer-term growth across world markets beyond 2020 indicates that export markets outside the OECD community could become more important, with the BRIC countries buying more industrial production robots, though not as many domestic service robots. This development may be some time in coming though countries such as India, Brazil and South Africa (and possibly Russia) may become export markets over the next decade for industrial robots with expansion of their car, truck, aircraft and railway production, and consumer electronics assembly. Specialist professional service robots for the commodities sectors will be important for these economies (e.g. Brazil is exploiting deep sea oil recovery in the Atlantic and is already using subsea robots) such as mining, pipelines, agriculture and logistics/transport. Domestic service robots may not be in demand in these economies.

Table 5.3: Forecasted future performance of major centres of robot production to 2020

	Japan	Europe	USA	Korea	China (& Taiwan)
Market share	May remain dominant; might be eroded by EU and China in basic types	Likely to grow - depends on new robot types' success for new segments: care, medical, SME etc	Static - remain dominant in military and space	High growth - mainly heavy industrial types and later lightweight and possibly domestic service	High growth. Assembles all the cheapest (service) robots today. Starting industrial robotics. High growth in components and at low-end; slower in more advanced. Source low-end white label
Growth rates in exports and in export base – the domestic market	Low/static until domestic service robot takes off in Japan	Low/Medium –depends on new robot types' success	Static except military and space	High growth from low base	High growth from low base at low-end of market
Qualified workforce numbers	Growing	Growing slowly	Static/low growth	High growth –educational efforts strong	Likely to grow very quickly
R&D expenditure in the sector and IPR holdings	Growing form high base	Growing from medium/high base	High growth (military - but possible spin-offs likely)	High growth from fairly low base	High growth from low base
Innovation potential	Medium	High	High	Medium	Medium
Costs to manufacture	Medium/high	Medium/low (E. Europe)	High	Low	Lowest
Commercialisation potential - industrialisation	Medium	Low – needs to improve	Medium	High	High/ very high
Strengths of clusters of users and suppliers	Medium	Medium - sporadic	Low/ variable (Detroit)	Medium	Variable – Taiwan high

Source: Authors' analysis.

Table 5.4: Market development - current and possible future market demand by robot type

	Japan	Europe	USA	Korea	China (& Taiwan)
Today's market	Industrial robots now, B2B market most important	Main market is in industrial manufacturing, B2B, small demand other segments	Develop own defence robots and consumer types. Buy in industrial robots and some military	Industrial robot market now, often indigenous products only	Main market is in industrial manufacturing and assembly, B2B, expanding, especially Taiwan
Tomorrow (2015-2020)	Service robots for elderly care; lightweight co-working and heavy industrial robots	Continuing market in industrial manufacturing Expanding markets in SME /co-worker market large enterprises; professional services; domestic service robots for elderly and healthcare	Remains largely military market with medium growth in industrial, professional services and domestic service. Some spend on elderly care	Industrial robots and domestic service robots developed for home market then for export. Some imports as competitors. Professional service robots.	Expand in all industrial types. PRC will become largest robot market with imports challenged by local production, either by global players producing in China (e.g. ABB, Hyundai) or indigenous new entrants

Source: Authors' analysis.

Looking to the future, new entrants must also be considered. New entrants to the robotics market are generally dedicated start-ups but there may also be those who will compete with robot suppliers from adjacent sectors. Key adjacent sectors could be consumer goods and electronics.

For instance, Google, Apple, Sony and Nintendo[73] may appear in this segment, perhaps oriented more towards mass consumption. Google's investment in Willow Garage with its open source hardware and software objectives is an interesting pointer to future directions.[74] Possibly Microsoft, with its Robotics Studio software as a development platform, is also a potential entrant to further parts of the value chain.[75] Sony has various humanoid experiments, robot toys and Playstations with accelerometers, as does Panasonic. Apple has strengths in user interfaces, operating systems, software for web applications plus strong competences in product engineering for user acceptance and global supply chain management.

5.3.5. Examples of potential new opportunity segments

The future position of the EU robotics industry will be determined by how well it competes at a global level in current market segments and by whether it can then move into adjacent key growth areas. There are certain applications which could be targeted by the industry. Segments that are likely to be attractive include:

- Food and drink: the largest demand may be from the food industry, Europe's largest industry, where over 90% of EU players are SMEs. By volume, some 50% of Europe's food comes from a few large food processors (e.g. Nestle) which exploit large-scale process robotics already. A major opportunity for robots is in food preparation and in harvesting.[76] Most of the simpler tasks such as palletisation have been covered already. Other robots for relatively straightforward foodstuff-assembly tasks have yet to be made and marketed.
- Environmental industries: for example in the manufacturing of solar panels and wind turbines, where demand has increased by a significant factor over the past five years and will continue, driving robot installations. For example, building laminated generators fast enough to meet demand will only be achieved by lifting and placing robots.
- Pharmaceuticals and biotechnology: these industries, populated by a majority of SMEs, are likely to be future users of robots which can co-work with human researchers and process operators, as in the food and beverage industry. Robots offer volume and cleanliness, essential for these types of flow process operations and specifically for testing large volumes rapidly and accurately. They also meet the demands for flexibility and easy adaptation to different tasks with smaller batch runs, as required by customers' changing needs.

Moreover, opportunities may well spill over from industrial robotics of all types (especially if lightweight, low-cost safe and soft) into the adjacent segments:

- For instance, for care of the elderly, the quest for a sophisticated multi-function robot that simulates a human carer is fraught with difficulty – owing to their complexity, expense and acceptability. Instead the EU industry could capitalise on the Asian interest in anthropomorphism by pursuing a strategic direction in simpler robots that cover the essentials well for a particular function. In terms of the industry basics to produce such machines, the comparative analysis above shows that the EU is on a par with its major competitors. Europe has an opportunity to be a global player, making simple service robots for the elderly both for its domestic market and for export.

73 Nintendo is included for its Wii games player, with its robust and low cost accelerometers and the possibility of adding actuators.
74 http://www.willowgarage.com/pages/robots
75 http://msdn.microsoft.com/en-us/robotics/default.aspx
76 Interview with Geoff Pegman, RURobots, UK.

- As noted above, industrial robotics technology could also be applied to the professional services market for cheaper robots. A prime example is service robots for inspection and surveillance, which could be used for infrastructure inspection of sewers and pipelines cable laying in ducts, cleaning services, etc. Here, domestic EU markets provide a good base for early sales and future exports.
- Co-worker robots will also inevitably be used by enterprises of all sizes, from larger companies down to SMEs, for manufacturing or logistics, and wherever handling and 'helper' tasks are needed.

EU strengths vary by Member State in production and in the take-up in the domestic market which could act a springboard for export sales. In terms of productive capacity of SME robots, there are clear leaders, for instance Sweden, Germany and Italy. On the demand side, in take-up by SME end-users,[77] France, Poland and Spain are strong.

Certain Member States (e.g. the UK) are further behind in terms of production of traditional industrial robots but are stronger in systems integration and subsystems. The reasons why certain Member States are further behind others include poor ability to follow long-term investment in the engineering sector, plus a scarcity of (and even reduction of) education for engineering and technology graduates, with no robotics specialisations at first degree levels.

5.3.6. EU competitiveness in robotics: SWOT analysis

Following the analysis above, the competitiveness of the EU's position in robotics compared with other regions and countries is summarised in a strengths/weaknesses/opportunities/threats (SWOT) analysis, as shown in Table 5.5.

Table 5.5: SWOT analysis of the position of the EU in robotics

Strengths • Well established and forward looking large manufacturers • Good systems integration capability • Strong software development capability and open source projects • Significant pre-competitive R&D expenditure at EU and national levels • Innovation high, in clusters, with successful rate of transfer to new end-users (especially SMEs) • Some technologies well developed and commercialised, e.g. safety products, vision systems	**Weaknesses** • Weak skills in non-manufacturing sector and SMEs • Lack of sufficient communication on robotics capabilities to raise awareness in the market • Moving from product innovation to commercialisation • Too few clusters – still nascent • Lack of technical standards • The EU robotics industry does hold valuable patents for robotics but does not have a complete set for all applications, so its IPR holdings could be stronger • Not competitive in base components for robotics (sensors and actuators) and electronics – largely sourced from overseas • Not competitive in low-end and white label mass production
Opportunities • Seed new robotic industry segment in the EU • Restore manufacturing of all kinds to be a growth industry in the EU by increasing manufacturing productivity • Long-term build of new markets in new user segments • Increase productivity for all sectors and sizes of enterprise	**Threats** • New opportunities taken by others if unable to bring innovations to market • Cannot maintain and expand in global market if lack skilled workforce- i.e. lack of degree level education, personnel training and apprenticeships • Products do not match expectations - rejection of robotics generally, if unsafe, too expensive or functionality too low

77 Results from SMErobot survey across six EU Member States.

5.3.7. Key policy issues for the robotics industry

From the above analysis, it is possible to identify the following key issues that an industrial policy for robotics for Europe should resolve:

- EU market entrants can have difficulties in moving from a working prototype to sales of a finished product, i.e. crossing the 'Valley of death'. In Europe, companies lack of support to do this and this is a key European weakness. In contrast, the transition is well covered in the Asian innovative support process and by the USA's military to civilian transfer (e.g. the iRobot instance). Support is needed for a successful industrialisation phase for new products, following innovation.
- Linked to this issue is the lack of venture capital support in today's and probably tomorrow's financial climate: innovative start-ups in Europe need more seed capital. Note that Robotdalen relies heavily on the national initiative in Sweden for innovation, Vinnova.
- Demand levels in all sectors of production need to rise, not only in manufacturing and large-scale players in capital-intensive industries, but also in SMEs. This requires increasing awareness of the fact that robotics can meet their requirements for productivity with flexibility. The market needs to be educated in what robots can do, how they can be used, and how they should be installed.
- Young start-ups need to gain better understanding of how to go on to the next stage after awareness and education, i.e. of how to sell and install, to create and then nurture a new set of markets
- There is a low level of intellectual capital in robotics in the EU workforce. The EU needs to resolve the issue of how to generate more graduates at degree-level in robotics and more qualified engineers, technicians and researchers in the workforce, both in the supply industry and in the end-user industries. As one major EU supplier remarked, there are many capable people trained in robotics in the car industry, but nobody has much experience or knowledge of applying this discipline in the food industry.
- Standardisation of interfaces, of the semantics of signals and the higher level building blocks used in robotics, at the level of plug-in functional modules (e.g. a vision system), and of whole robots with standard interfaces and supply requirements is needed.

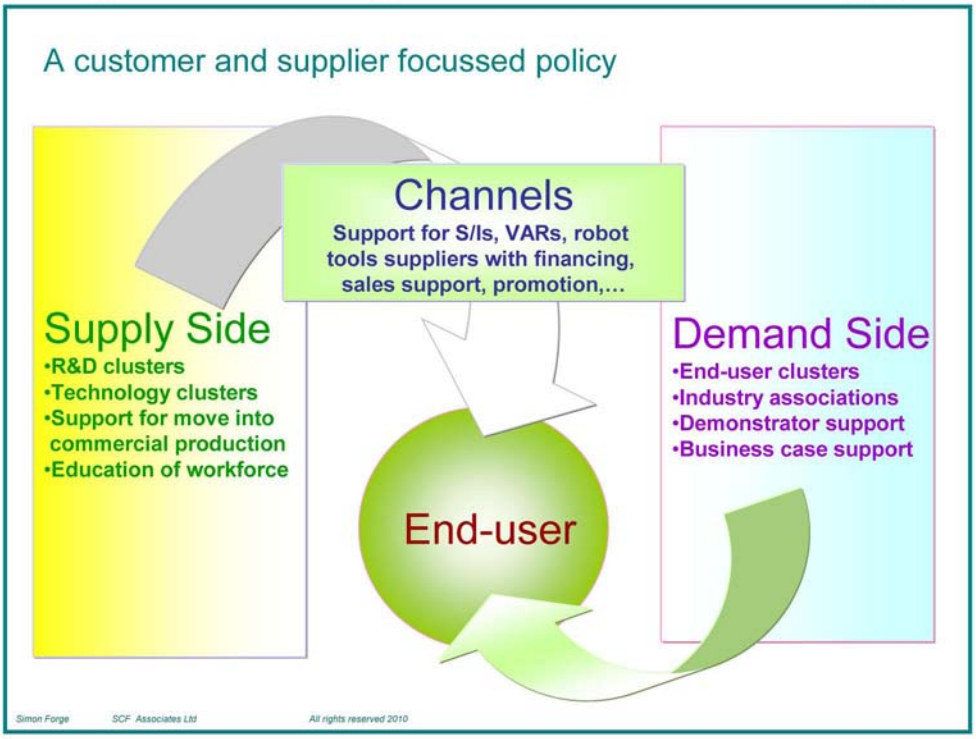
5.4. Policy implications for the EU

5.4.1. Principles for shaping an industrial policy

This report concludes that the way ahead for the EU robotics industry is to become primarily an exporter, having first built up strengths on the domestic market. Policy should ensure that European firms can compete with leading global suppliers – i.e. those from Japan, the USA, and Korea, and in the future, the leading the BRIC nations (in particular China) in technologies and production by:

- Aiming policy actions at the domestic market's demand side also, not just the supply side (as shown in Figure 5.3). This includes understanding the bridge between the two, i.e. exploiting the role of the multiple channels to market.
- Ensuring that policy actions address the top layer of added value – design and engineering – with a more intense focus on production, including materials and sub-assemblies. This approach would accept that the lower value, basic electro-mechanical and electronic components are likely to be sourced globally and not necessarily be part of the European value chain. It is a

Figure 5.3: Policy should aim at a support framework for demand and supply sides



strategy of accepting weaknesses, where a local solution is not viable, and also reinforcing the strengths.

- Focussing marketing efforts on the largest unexploited opportunities, e.g. food processing, high technology industries, professional services and domestic services.
- Helping to build a strong domestic market in new customer segments for two reasons: first, to equip the emerging user segments (care, SMEs, etc) with the means to enhance the EU's own general productivity; and, second, to establish robust models and experience before pursuing export markets in the longer term.
- Creating a support infrastructure for industrialisation and commercialisation of new developments.

5.4.2. The tactical goals for industrial policy for the next five years

From the previous analysis on competitive positioning and strategy, the tactical issues that an industrial policy for Europe must tackle to achieve the roadmap above are:

- More clusters to support innovation and introduce new end-users,
- Education programmes for more qualified engineering graduates and technicians,
- More support for the industrialisation phase after innovation – the 'Valley of Death',
- Training and introduction/awareness building support for end-users of all sizes,
- Increasing the likelihood of innovation with more venture capital support,
- Standard robotics platforms for plug and play, with pooling of IPR or open IPR,
- A complete legal framework for widespread deployment.

Expanding further on the above, some key points to consider include:

- Stimulation of user demand implies understanding what end users (such as SMEs) really need, with demonstrations of appropriate types of robotics in each application area. It also implies support for business case analysis during the introduction process.

- A priority area is training and education of researchers, system integrators and technologists.[78] Robotics engineering is especially difficult as it requires a multi-disciplinary approach. It requires expertise across mechanical, electronic and electrical engineering, materials science and software, plus several branches of computer science. Creating a skills base through degree level education is essential both for primary technology research and for implementation, via systems integration. Here, the EU lags slightly behind the US and Japan in core competencies in education for the most advanced technologies taught at degree/apprenticeship level. Robotics engineers will be in demand not just from the robotics industry supply side but also increasingly from the end-users, both large and small. Collaboration between universities and Europe's leading robotics suppliers is well developed and should now expand into the user side.
- As systems integration is often a larger part of the value added than the robot itself, innovation in technologies explicitly for systems integration, especially standards that support integration, is likely to bring faster deployment of robotics technology. S/Is tend to quickly form around such technology opportunities. This may in reality imply a public pooling of key IPR, as happens in the mobile communications industry, to enable standard robotics platforms for plug and play. This could encourage a 'GSM-type' market in robotics, through pooling of IPR, or open IPR, for software and interfaces to sensors and actuators and for the higher level 'semantics' of robot applications, e.g. in machine vision. Such efforts could lead to a common open technology platform and would help build an ecosystem of software, complete applications, integrators and tools and drive the VAR market. It would also enhance the capability to bring innovations to market quickly, based on standards for plugging in new components flexibly. In turn, this would increase the IPR holdings in specialised applications and equipment, built on top of the common platform. The patents portfolio in the EU does not cover all technologies and devices, meaning EU suppliers have to licence some items from overseas, but this is equally true for each competitor nation. The important point is to have IPR to trade for items needed.
- Building up the indirect channels is important for attracting new end-users, such as in the SME segment, because a strong bridge between supply and demand is a key enabler of sales. Tactical goals include supporting the channels map (see Figure 2.13) as the end-user is most likely to be educated and reached via a number of indirect channels. The route to market has to be understood as part of policy actions to support the introduction of robots. Such a policy is fundamental to the SME segment but also applies to new markets – green industries, food processing, agriculture, etc. It should be complementary to the various forms of aid for technology innovation, i.e. effectively, for the supply side. Such an approach implies using a model, adopted by some Asian countries, of doing more than simply providing 'seed corn' R&D support in a pre-

78 Interview with Antonio Bicchi, University of Pisa.

competitive role. It means helping value-added resellers (VARs), system integrators (S/Is) and tools suppliers (often resellers), plus independent software vendors (ISVs) as these are the key links in the routes to market, and not just the core robot supplier with the associated technology producers.

- The legal and commercial context of future robotics needs to be put in place, in advance of the technology, in three key areas:
  - Legislation on health and safety – the rules governing deployment of robots. Although there are various industrial standards from ISO and others, the real problems may come from applications in medical, care and domestic situations. Asimov's laws need to be taken seriously and developed in practical ways here.
  - Security and privacy for use of robots with humans – e.g. introduction of viruses could cause major problems in industry and especially in care and domestic situations. There are also strong privacy concerns, in that the robots could be used to give information about a person or home; this could be a breach of privacy rights.
  - European IPR protection for worldwide markets – as mentioned above.

5.4.3. Recommendations for policy actions

If the EU is to capitalise on the opportunities now emerging, policy action is required before others seize the initiative. Key policy recommendations are given in Box 5.1. These recommendations focus on building up the EU's top layer of added value – design and engineering – with more intense efforts to arrive at commercial production from innovation by helping commercialisation. This requires that a stronger 'eco-system' is built up as soon as possible.

5.4.4. In conclusion

Creating a European robotics industry needs an active policy programme based on a strategy which envisages a future robotics industry with multiple sub-segments. Policy actions should expand both the existing industrial manufacture of robotics, and more importantly, nurture the new potential markets. The key new segments are the SME and professional services markets and, in the longer term - perhaps after 2020, the domestic service markets. As emphasised above, this also means stimulating the demand side, especially the SMEs among the new kinds of end-users, who may have never considered using a robot before. To sum up, policy for the future industry requires actions that are targeted not only at the OEM supplier and the demand side, but also at the whole eco-system and channels to market that link both sides. It involves clustering to support new end-users as well as producers.

Box 5.1: Key policy recommendations for developing the EU's future robot industry

- Promote a cluster strategy which would support the new end-users and innovative new suppliers. The Robotdalen cluster in Sweden could be used as a model and extended across the leading Member States. Financial support should be provided, with a range of measures, from financial support for a business case, to low-interest loans for science parks and 'villages', to formation of interest groups of users.

- Help innovative entrepreneurs through the 'valley of death' –i.e. through the phase of industrialisation, post-innovation and the first prototype, i.e. moving from the first working model into commercialised models and then into commercial production.

- Expand education in robotics engineering as a long-term strategy with a pay off only after 5 to 10 years. A combined degree is needed which would embrace mechanical, electrical, electronic and hydraulic engineering, advanced materials, computing hardware and system software and utilities/ cognitive/digital signal processing/application software. A successful course of this kind would require student support; faculty set up; on the job training; vocational apprenticeships; and postgraduate research centres of excellence distributed across EU with specialisations, e.g. visual processing, materials science, muscular mechanics, etc.

- Raise awareness of the capabilities and benefits of robotics among end-users generally in the EU market and in specific segments of end-users with promotion and communications to stimulate demand and training support for SMEs. A key part of this would be support for vertical segment demonstrator projects, encouraging new end-users by showing what can be done and at what cost with what risk.

- Build an EU wide eco-system with local presence in each Member State, through:
  1. Education of systems integrators (S/Is) with awareness building, then training courses for a long-term build of a support ecosystem for end-users. The aim would be to create a strong S/Is industry of knowledge workers, with high skill content for introducing robots and in vertical applications, also driving high-tech employment and combat the limits on S/Is set by their capability and their commercial risks.
  2. Support for all channels to market, i.e. VARs, ISVs, S/Is and for the robot suppliers, i.e. support for the European channels map.
  3. Encouragement of key technology suppliers (e.g. machine vision) through the cluster strategy.

- Encourage competition amongst robot suppliers and technology innovators with support for new entrants, start-ups and high-risk ventures to develop new technologies.

- Provide financial incentives for R&D and innovation in key areas, such as mechanicals, materials, and software for human-robot interaction, especially natural language processing and cognition, robot operating systems, signal processing, vision systems, simulation packages, communications, etc, as given in Tables 2.3, 2.6 and 2.8.

- Promote standards in robotics through standard interfaces for software and hardware applications library with open source software for each segment (cf. Willow Garage supported by Google). This would support the system integration process, encourage competition and lower the costs to end-users in both integration and purchase. The analogue of a robotics industry like the early PC industry, where all suppliers could build to a common platform, is a valuable goal.

- Support extension of current innovative developments into a larger professional service segment, and in the long term, care and domestic service segment, through to commercialisation of products.

- Support the development of a complete legal framework –to be put in place before the technology– covering robot safety, security and privacy, with protection and/or pooling of IPR to build standard platforms.

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Glossary

Term	Definition
Accelerometer	Device for measuring acceleration, often electromagnetic/piezoelectric
Actuator	Device that converts energy into motion so that a robot can move – several different energy types are commonly used e.g. electromagnetic, or pneumatic or hydraulic
Articulated robot	A type of robot whose arm has at least three rotary joints
Bio-mimetic	Robot imitation of the biological systems occurring in nature
CAD	Computer-aided Design
Capex	Capital expenditure
Cylindrical robot	A type of robot that has axes that form a cylindrical coordinate system
HCI	Human-Computer Interaction, analysis of the relationship of computers and humans
IPR	Intellectual property rights
ISV	Independent software vendor
ITV	Independent tools vendor
Linear robot	Linear or Cartesian or gantry robots: an arm with three prismatic joints with axes that are coincident with a Cartesian coordinate system
MICE	Miniature internal combustion engines
OEM	Original equipment manufacturer
Opex	Operational expenditure
NACE	Nomenclature of EConomic Activities.
PLC	Programmable logic controller
Proprioceptor	A sensory receptor, found chiefly in muscles, tendons, joints, and the inner ear, that detects the motion or position of the body or a limb by responding to stimuli arising within the organism
SaaS	Software as a Service
SCARA robot	Selective compliant articulated/assembly robot arm – a type of robot consisting of two concurrent joints that rotate within the same plane
SDK	Software development kit

S/I	Systems integrator, a specialist company that merges robots, peripherals, and manufacturing machinery into a production system that functions as a single unit to perform manufacturing tasks
UAV	Unmanned aerial vehicle
VAR	Value added reseller
Work cell	Pieces of equipment within close proximity that all work on the same production activity

List of experts interviewed during the CEROBOT study

Interviewee	Affiliation
Antonio Bicchi	Professor, University of Pisa, Italy
Jeff Burnstein	President, Robotics Industry Association, USA
Rodolphe Gelin	Engineer, Aldebaran Robotics, Paris, France
Birgit Graf	Manager, Domestic Service Robotics, Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), Germany
Martin Hägele	Head of Robot Systems, Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), Germany
Martin Hancock	Technical Manager, Newfield Ltd, UK
Theo Jacobs	Research Manager, Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), Germany
Clive Loughlin	Editor, Int. Journal of Medical Robotics; Journal of Industrial Robotics, UK
Erik Lundqvist	President, Robotdalen, Sweden
Ulf-Goran Norefors	Business Development Manager, ABB Robotics, Sweden
Niklas Olsson	Technical Manager, Solo Mechanical Solutions, Sweden
Geoff Pegman	Director, RU Robots, UK
Richard Piggin	Consultant, Network & Security Services, Rockwell Automation, UK
Stephen Von Rump	Managing Director, Giraff Robots, Sweden
Anne Wendel	EUROP Secretariat, Belgium
Ken Young	Professor of Robotics, Warwick Manufacturing Group, Past President British Automation and Robotics Association, UK

Appendix 1: Methodology for the study

The objective of the project was to analyse the future competitiveness of the EU in robot technologies. The study, carried out between September 2009 and July 2010, began with a general techno-economic analysis for the whole field of robotics. Following this, two areas were chosen for further study. In a third and final step, the competitiveness of the European industry in these two areas was assessed and policy–related conclusions were drawn. These steps are described in more detail below:

Step 1: General techno-economic analysis

The first step comprised a techno-economic analysis of the overall robotics set of technologies. This included:

- definitions of robotics,
- identifying the state of the art (what are the constituent technologies, how they work),
- analysing further technological development (what could they do in the future and what are the technological gaps/roadmaps),
- identifying existing and potential applications (what can they do, what might they do tomorrow),
- assessing their market potential (market size today and in future, main geographical and applications/technologies distribution),
- identifying major robotics industrial players and clusters,
- identifying the major value chains,
- assessing the disruptive potential of the various areas (technologies/applications) of robotics.

This was carried out through a mix of desk research and interviews with industry experts. The findings of Step 1 were presented in an Interim Report, available as a separate Annex to the Final Report.[79]

Step 2: Selection of areas for further study

In this step two emerging and potentially disruptive areas of robotics were chosen for further analysis. The findings of Step 1 were presented at a project workshop in which several potential areas were considered before two areas were selected – safety in robotics, and robotics for small and medium-sized enterprises (SMEs). These were chosen according to two criteria:

- First, the potential size of the market, and
- Second, the capability within the EU to capitalise on the opportunity.

Step 3: Competitiveness analysis

The third step consisted of an in-depth analysis of these two areas. It began by deepening the general techno-economic analysis developed in Step 1 through further interviews and desk research. Following this, all the study's findings were analysed to provide an assessment of the competitiveness of the European

79 See: http://is.jrc.ec.europa.eu/pages/ISG/COMPLETE/robotics/index.html

robotics industry regarding SMEs and safety. Finally the study identified areas where European policies could have an impact on competitiveness of the EU industry in this regard. The study's findings were then presented and discussed in a validation workshop with industry experts and European Commission staff, comments from which were incorporated in the final report.

European Commission

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Abstract

This report is one of a series resulting from a project entitled 'Competitiveness by Leveraging Emerging Technologies Economically' (COMPLETE), carried out by JRC-IPTS.

Each of the COMPLETE studies illustrates in its own right that European companies are active on many fronts of emerging and disruptive ICT technologies and are supplying the market with relevant products and services. Nevertheless, the studies also show that the creation and growth of high tech companies is still very complex and difficult in Europe, and too many economic opportunities seem to escape European initiatives and ownership. COMPLETE helps to illustrate some of the difficulties experienced in different segments of the ICT industry and by growing potential global players. Hopefully, COMPLETE will contribute to a better understanding of the opportunities and help shape better market conditions (financial, labour and product markets) to sustain European competitiveness and economic growth.

This report deals with robotics applications in general, and in two specific areas selected because of potential market and EU capability in these areas: robotics applications in SMEs, and robotics safety. It starts by introducing the state of the art in robotics, their applications, market size, value chains and disruptive potential of emerging robotics technologies. For each of the two specific areas, the report describes the EU landscape, potential market, benefits, difficulties, and how these might be overcome. The last chapter draws together the findings of the study, to consider EU competitiveness in robotics, opportunities and policy implications. The work is based on desk research and targeted interviews with industry experts in Europe and beyond. The results were reviewed by experts and in a dedicated workshop.

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