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Influence of the new trends in the economics on the military and industrial robot system design philosophy

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INTRODUCTION

THE SCIENTIFIC PROBLEM

Robots are a part of everyday reality. Their presence and abilities are ever growing and they are transforming our future. Although much academic research has been done on the many challenging technical aspects of robots, little research is made on the social, geopolitical and economic factors that drive this industry ahead. This thesis will focus on the role and purpose of robots in human societies, both from an industrial and military perspective. The way industrial and military robots are positioned in 2010-2012 will allow making conclusions and identify trends forecasting about their future.

Automation started in the earliest human societies with automata, tools to assist humans in their tedious and heavy tasks. The last 20 years however automation and robotics has taken an enormous leap forward in its use and application. My research aims to determine how robots and their use - as part of flexible automation - have influenced society since their beginnings many centuries ago and how inbred human fear of machines is being dealt with. Also I look at how robotics is spreading within society and the various industrial sectors and how this will influence future development of industrial robots and linked sectors such as military robots.

I limit the scope of my active research to the industrial and military robots, while only touching the areas of service robots, humanoids and androids, among others. While there is an official classification of industrial robots, no such thing exists when it comes to the military robots. My analysis of the various goals of the numerous types of military robots allowed me to draw up a clear segmentation matrix. This military driver matrix allowed me to define military robots within their groups and simplifying research on trend analysis, exposing limitations and predicting future development.

Robots started to find their right of existence with the use of articulated robots in the automotive industry. First applications were to be found in the material joining area: spot welding and arc welding in car factories. With the spread of automation into other industries, robots were being used in different applications like machine loading and material handling. The last decade industrial robots are being used in all industries but still predominantly in automotive industry.

Sectors like electronics manufacturing, food and beverage, metal and general industry can be named here. Since 2010 new industrial sectors are identified for robots like aerospace and the medical sector. The experience gained from the use of robots as tools in industrial automation is transforming the industry itself, putting new challenges on robot design and the way of production. Hard data from industry shows that there is still a massive growth projected for the coming decades for industrial robots. Also technology is marching forward, and with it the field of robotics. To determine the future of industrial robots I used economic modeling tools like the Product life Cycle and Concentration Curve to base and test my research hypothesis. These models clearly show the maturity of the industrial robot, which will lead to its technological diversification. The experienced growth by industrial robots will likely continue while the high market concentration limits newcomers to niches. How the adaptation of robot-use occurs within companies in industry has never been analyzed. To understand the areas for growth within industry it is paramount to understand how robot-use grows within a company. For this I constructed a Robotics Growth Process model. This model approaches the adaptation by a given company with respect to the use and application of industrial robots. Based on the available usage data, experience and interviews it allows making predictions on future robot use within the various industrial sectors.

To analyze the current spread of robots and its trends I have used an approach using density charts. These charts map robot density per region and per industrial sector and allow looking ahead in time based on previous results. I have analyzed expenditures in R&D (Research and Develoment) to expose the geopolitical trends related to robotics. While Japan has been traditionally the birthplace of industrial robotics, its leading position is being challenged by upcoming powers like China. Large growth can be expected in many industrialized nations, as upcoming industrial nations need to close the density gap with the leading nations in order to stay competitive. Robots are not only changing the industrial landscape but also the competitiveness of countries and regions. To predict the competitiveness of regions I analyzed robot sales volume related to car manufacturing. The result shows clearly the automation gap in the United Kingdom, while investments and future growth in robotics by BRIC (Brazil, Russia, India and China) countries is evident. The world’s average robot density is 51 robots per 10.000 employees. Japan is by far the most automated country in the world with a robot density 6 times that of the world’s average. But new markets are emerging quickly, especially in Asia, where Korea and China are growing in a fast pace. It is predicted that China will overtake Japan in annual robot installations as early as 2014. The data suggests that the rise of a national Chinese robot manufacturer can be expected. Germany makes up 50% of the European market and plays a crucial role in the old continent. The annual compounded growth rate since 2002 till 2012 in industrial robot sales amounts to 7%. A strong grow rate, which will continue for the future.

Most western societies face a growing share of a 60+ aging population. This group will in fact be one of the largest demographic groups, reducing the available work force. Part of my research has been dedicated to the correlation of the aging of the population in developed western countries as well as in upcoming powers like China with respect to robotics. To understand the implications of aging on the future trend of robotics I have designed a model where robot density and population aging are correlating. It pushes the emergence of the field of Service Robotics, which in 2012 is still in its infancy. Prototyping exists but large-scale commercial rollout has not yet happened. Either Japan or Korea would be the number one candidate here.

To understand the future of industrial and military robots it is necessary to analyze and understand which impacts it had on human societies. For this I reviewed the human fear for machines and intelligent life forms, as well as the effects of design on their acceptance. The uncanny valley analysis showed that a too human look-alike form has a negative impact on the adaptation. Also the ethical approach on how robots should behave has to be taken into account as it shapes their functionality and degree of autonomy.

The western capitalistic model drives manufacturing costs down by using flexible automation in the form of robotics. It is an unstoppable spiral, where machines and robots take over basic jobs massively. This implies possible high unemployment and the need for a new attitude on society and education. In total there are more than 1 million industrial robots in operation in 2012. To understand where this leads to, I analyzed the effect of the use of robots on the labor market. Although there is a direct negative effect on the share in manufacturing, the total employment is not (yet) effected. The welfare of humans comes under attack if no shift to higher education, R&D and creative innovation is undertaken. Artificial intelligence and robotics are not a threat, but should contribute to a more sustainable society.

Using the economic life cycle modeling I could determine the factors that prolong the growth cycle of industrial robots and I have identified three new design application areas being the lightweight robots, the 7 axis articulated robots and the 6 axis delta robots. To make valid statements and predictions about these innovations and to better understand these shifts in market and technology, I needed to define a new market model. This robotics matrix tool allows me to better understand the constraints and opportunities in the quadrant where robots and humans interact fully and freely together. This segment has so far been out of reach of robotics. Industrial robots typically do not cooperate with humans. The robotics driver matrix identifies the growth paths of industrial robots. With the entrance of robots in the new area of human-robot cooperation a broader view is necessary. Aside from the technical aspects on the robots themselves, adaptation of the workplace and the spectrum of interaction, or communication with the robots are new factors and fields for further investigation.

When I analyzed the constraints and limitations on the military side, it shows that there is a complete lack of functionality when it comes to the ethical side of their use and responsibility in the case of autonomous assault robots. Hence a possible trigger for an adaptation in their technological development. Technical limitations like energy supply, target discrimination and environment complexity also shape their future design. The predicted sales volume for military robots for 2020 with 9 billion US$ is just staggering. The share of UAV (Unmanned Aerial Vehicle) make up to 45% in 2010 of all spending on military robots.

RESEARCH AIMS

My goal was to research the influence of broad economic trends on the future design philosophy of military and industrial robots. In this context I apply a holistic approach of the economic impact, growth and market characteristics.

I have set out the following tasks:

1. To analyze the application and history of industrial and military robots to determine their current market structures and properties in order to identify new innovation trends.

2. To determine the effects that industrial and military robotics have had on human societies. Identify the relationship between these effects and future use and application.

3. To examine, model and realize a new segmentation of military robots that could identify limitations, common functionality and research waypoints based on the desired objectives of these robots.

4. To examine the effects of aging populations in societies on the adaptation and use of robotics correlated to the competitiveness of countries.

5. To investigate the effects that robotics has on the labor market.

6. Utilizing a new matrix model for industrial robots, identify the new design philosophy paths and propose future human-robot interface possibilities and workplace adaptations.

RESEARCH HYPOTHESIS

The following fundamental scientific questions are to be posed:

- **Question 1:** Can a complete new design of industrial robots be expected? (Related research covered by Chapter II, III and IV)
- **Question 2:** Is there a future for Light Weight Robots? (Related research covered by Chapter IV)
- **Question 3:** Is Robotics creating or destroying Labor? (Related research covered by Chapter I and II)
- **Question 4:** Is there a fundamental economic proof that supports future growth of industrial robots? (Related research covered by chapter III)
- **Question 5:** Can military robots work fully autonomously? (Related research covered by Chapter III)

RESEARCH METHODS

For analyzing the numerous professional references and publications found in libraries, magazines, business publications and Internet, I used the method of analysis, cross-referencing, modeling, synthesis and deduction. Working as a professional in the robotics industry gave me in many cases the opportunity to verify claims and statements in real applications.

The creation of hypothesis and research questions were based on my professional experience in the matter of robotics and the raw statistical data provided.

I have visited various international trade fairs, like ‘Automatika’ in Munich (D), where all international robot manufacturers, robot sensor and robot peripheral companies and experts expose, confer and gather.

I have conducted interviews with various high-level executives and experts of many of robotics related companies and research institutes to get qualified input on the direction of their research and to test my hypothesis. On top I have conducted interviews with well-known scientific robotics researchers.

Over the last 15 years I have participated in various international scientific and industrial conferences and platforms, often as a speaker, pertaining to the subject of my dissertation.

As a result I have gained a deep knowledge of the subject, able to draw conclusions based on both verifiable quantitative data combined with qualitative input. Hence my achievements have been published by various professional technical academic journals, as listed in the list of publications.

PROSPECTIVE SCIENTIFIC RESULTS AND EXPLOITATION

New scientific results will be considered as follows:

1. I examine and analyze the types of industrial and military robots used worldwide, and with this basis, will prove market growth despite the maturity status.

2. I will investigate the viability of new developments like 7 axis articulated robots, 14 axis dual arm robots and Light Weight robots. It is determine if to these new innovations can be considered as new growth areas within the Product Life Cycle.

3. I research the negative attitudes and concerns about the use of robots and the human fear for machines.

4. I will analyze the impact of using industrial robots on labor. I want to prove that there is indeed a negative impact on the manufacturing share.

5. To understand the evolution of industrial robots I will design a new framework. Where I systematize industrial robots according to production flexibility and assembly complexity.

6. I will determine that for the human-robot collaboration segment a mere focus on robot hardware design is not sufficient.

7. Requirements analysis need to show if standardization on the programming language and safety related issues is a priority with the development of human-robot collaboration.

8. I will analyze the currently deployed military robots, based on their manifold objectives. I will create a matrix by systemizing military robots according to their level of impact on the human and economic side.

9. I will analyze the position of military robots in society.

10. In order to predict future military robot design I will analyze the constraints on military robots.

11. I will determine basic requirements concerning the technical and ethical aspects of future military assault robots.

CHAPTER I: ROBOTS IN HUMAN SOCIETIES

In this chapter I will establish the current position of industrial and military robots in human society. A thorough understanding of what means robotics in 2010-2012 is paramount before any statements on trends and new design philosophy can be made. The conclusions will serve as the basis to analyze the research aims for the next chapters. Also I will investigate here the history variety of military robots used. While industrial and military robots differ in purpose, design, form and function they share many elements and historical paths. As an industry military robots are lagging behind their industrial cousins, but are catching up quickly. It implies to deal with basic questions concerning robots used in the military theatre, it being a relative young and emerging sector. An official classification of military robots does not yet exist and the term robot is widely used and abused. In the case of industrial robots an official ISO (International Standard Organization) classification does exist, so the question is how to analyze military robots and derive trends, identify problem areas and find common characteristics. Can a common denominator be found and used for segmentation of military robots? Before these questions can be answered basic definitions, history and economic positions are to be dealt with.

1.1 Robots in Human Society

Automation has deep roots, going back to the early days of mankind. Robotics is a logical result of the industrial revolution that started in the late 18th century in England. The Industrial Revolution de facto changed the economic scene as per-capita economic growth was realized in the western economies. It started the current capitalist economies. A relevant fact, as all historians are in agreement that the onset of the Industrial Revolution is the most important event in the history of humanity since the domestication of animals and plants [1.1]. One development worthwhile mentioning is that of machine tools. The textile industry which was at its heights in the late 18th century employed craftsmen from the watch and clock sector to develop machine tools to be able to produce parts necessary for the automation of textile machines. Machine tools enabled to produce machines made out of metal in an economic way, instead of using manual labor on wood and steel and thus became the stepping stone for ‘modern’ engineering and flexible automation using robotics [1.2].

It was the automobile industry that embraced robotics in the mid-20th century. In 2010 more than 77 million cars were produced worldwide [1.3]. A staggering number indeed, providing the home for many industrial robots in applications like spot welding, arc welding and handling, among others. In fact, many current well-known industrial robot suppliers found their origin within one of the car manufactures' automation departments. The current biggest manufacturers of robots are 1, FANUC, that was emerged out of a joint venture between the robotic divisions of GM (General Motors) and FANUC Ltd, while 2, the German based robot manufacturer Kuka, grew out of the Volkswagen Automation department and 3, the Swedish/Swiss group ABB (Asea Brown Boveri) that was created partly from Renault automation.

1.1.1 Definition

To define the scope of my dissertation it is rudimentary to define what is in general understood as a robot. A robot is (still) a man-made mechanical device that can automatically perform certain tasks following a set of pre-programmed decision rules. Humans and or the environment interact with these programs that were introduced earlier into the robot. Control is handled by a set of general rules, which are converted into action allowing the robot using artificial intelligence techniques. By this definition a robot differs from a numerical machine, programmed only for a single task. **Robotics** is a science that studies and develops robots. The main task of the robot is to replace humans at more often than not repetitive activities, where the robot can perform better than humans. The domain of their applications is also at tasks that are dangerous to humans. The latest 10 years show a growing trend of robots taking over functions that were done by traditional machines or hard automation. First I look at their history and origins, in order to determine the current status in human society.

Labor costs reduce when applying (articulated) robots. Robots reduce direct manufacturing labor needs, improve labor deployment and can decrease indirect labor costs. Also important to mention are the improved ergonomics and worker safety. Humans can be removed from hazardous and unhealthy processes by using robots. Examples like exposure to hazardous gases, acids, extreme high and/or low temperatures, lifting heavy weights, or avoiding strenuous repetitive motions that provoke injuries can be mentioned here. It is a myth however those robots will eliminate all production labor costs. In reality I can state that robots are not panaceas; there are jobs for which people are better than robots. Think also about employee training and turnover. Indirect labor costs are also positively affected when using robots. There is a substantial reduction in HR (Human Resource) related costs when using robots in a production line instead of human labor: less cost for hiring, training, safety clothes and equipment etc. These hidden costs are often forgotten while calculating the ROI (Return on Investment) on robot related investments.

Even with the crisis at hand and the rising pressure from so called low-cost countries many small company owners still think that robots are too expensive to set up and to maintain. Reality is different however. As with personal computers, prices have declined over the last 15 years while ease of use and performance has improved. Robots are now to be considered as commodities. And thanks to the powerful evolution of CPU's (Central Processing Unit), the programming of robots is surprisingly easy. Line operators can take ownership of these flexible automation solutions and improve the robot performance thanks to their knowledge of the underlying process. And it is not only high production runs that can justify robot costs. Robots can perform different tasks for different parts while hard automation usually is limited and often needs more time for changeover. What's more, integrated vision in articulated robots are allowing the robot to see. They capture images and processing the data into information for the robot and by the robot. No more need for costly and unreliable PC (Personal Computer) driven systems and interfaces. And what is not there cannot break down and stop the line! It also greatly enhances the reliability and thus throughput of the line.

The last 10 years have shown an enormous interest and growth in handling primary food: robots handling the raw/fresh product. The driving question here was: how to cut back on the rising labor costs while maintaining line flexibility? For articulated robots to actually work in the food production and thus be in direct contact with any kind of food implies a compliance with local conditions in the food sector. Food can be characterized as a non-uniform product, not having clear standards, hence a showstopper for robots. Second is the hygienic component; are industrial articulated robots suitable for use in primary processes? And lastly the environment within the primary processes is harsh: how are robots withstanding the various cleaning and disinfection processes? In addition to the possible presence of salts, alkaline, acids just the simple fact of hosing down a robot with water under pressure will definitely put it out of business. Extreme high and/or low temperatures or fluctuations also play their part. FANUC, being the world’s largest robot manufacturer, came up with a new way of looking at robot design. It resulted in robots with smooth surfaces, adapted sealing, white body color and epoxy paint, plastic covers instead of steel, and food grade grease in the mechanical unit. These robots, also known as food pickers and available since 2008 comply with above mentioned conditions and reshape the current industry. These food pickers, with 5 degrees of freedom can now be found in large numbers handling cookies, dough, chocolates, frozen fish and many other primary food products.

1.1.2 Origin and history

The word “robot” is used and recognized worldwide, and has first been used in the year 1920 by the Czech play writer "Karel Čapek " in his theater play called R.U.R. or "Rossum's Universal Robots." In Czech language the word "robota" means to (obligate) work. In this theater play, Karel Capek named a slave that could only work a "robot". Karl Capek’s brother Jozef [1.4] made up the word robota. Not by coincidence were the robots in the play invented by a man called "Rossum" which refers to "wisdom" in Czech language. Even in 2012 an acceptable definition of robot is that of an intelligent working machine. The general public associate robots with science fiction, like in the books of Isaac Asimov and movies like Star Wars, Terminator, I Robot and Robocop. More than often the displayed robots have a humanlike metallic shape and possess a high level form of artificial intelligence. These kinds of robots are classified as humanoids. When it is unable to distinguish humanoids from humans they are also called androids.

The word ‘robot’ in the 21st century has become a generic term. Apart from the real technical sense it is often being used for marketing purposes to describe any semi-automatic apparatus that somehow should appeal to the public. Many examples here can be named: food robot (for grinding food into small pieces), garden robot (for semi-automatic cutting of lawns), and a big category of remote controlled toys. The history of robotics and automation however has its roots much deeper in civilization.

Around 1600 to 1400 BC (Before Christ) the Egyptians and Babylonians invented water driven clocks. Most probably these were the first human attempts to automate. These ingenious instruments belong to the constant outflow types. Small holes in water tanks dripped at a constant rate, measuring time by the decreasing water level inside the tanks. There was presence of different tanks for the different months [1.5]. In consecutive years these developments were greatly enhanced by the Greeks and the Romans. Mechanization was added, as well as dials and indicators. It was the ancient Greeks that came up with the word *automata*, to describe water clocks, tools and toys and derivative machines that would operate automatically.

Robotics is also often described as "**flexible automation**", referencing to the early beginning. A name I would like to recognize here is that of an inventor from Alexandria called Heron, who designed an automated cart, water engines and siphons among other [1.6]. Using strings and dead weights, Heron made it possible, as with current robots, to move a 3-wheel cart forward, backward and stop, based on a predetermined programming. Another major noteworthy breakthrough in robotics and automation came from the Arabic world. In the year 8, three brothers from Persia issued a publication, also known as *Banu Musa* (Ahmad, Muhammad and Hasan bin Musa ibn Shakir). Their book called "Book of Ingenious Devices" described a hundred or so automated devices [1.7]. Although some of their inventions were based on Heron's work, many were theirs and involved delay systems and conical valves, pneumatics and the use of non-moving gases. They invented various fountains and also the first mechanical music instrument; a water-driven organ to mechanically reproduce music sets.

It would take till the 19th century before major improvements were made on the Banu Musa's design [1.8]. It was Blaise Pascal that made progress on mechanical calculators from 1642 onwards. Pascal's calculators, he made more than a 50 variations over 10 years, were the forerunners of computer engineering, the intellectual backbone of robotics [1.9]. In the 18th century sir Richard Arkwright can be credited as being the forerunner of the now known industrial revolution. It was Arkwright who invented and developed the automatic weave and spinning machines and employing them in his in own factories, first using water power, later steam engines [1.10]. Later, in the 19th century it was the English Charles Babbage that invented an Analytical Engine, following the work of Pascal. His invention could use loops, independent programming via punch cards and had I/O (Input Output). Although his machines never left the prototype stage, models built based on his design 20th century showed that his results were accurately up to 31 digits. In fact the first mechanical computer was born [1.11]. Another English scholar, the mathematician George Boole, laid the basis of digital computer logic. Robotics in 2012, if seen as a mere result of all developments during the Industrial Revolution, has next to the logic/computing side also a mechanical/drive side.

Drive systems have their roots founded by a Serbian mechanical and electrical engineer named Nikola Tesla, born in the year 1856. It was Tesla that invented the induction motor, the first electrical motor to run on alternating current. His work also contributed to the development of radar, remote control of vessels and nuclear physics. Electric motors now take up the vast majority of actuators in robots, AC (Alternate Current) servo for industrial robots and DC (Direct Current) in portable robots. Servomotors use negative feedback loops or control systems.

1.1.3 Industrial Robot Definition

In the industrial market place many types of robots are present, but not every robot is to be considered an industrial robot. The definition of an industrial robot has been worldwide agreed upon via ISO. The Industrial robot as defined by ISO 8373 [1.12] is an *automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications.* For completeness sake it is necessary to sub-define the various elements of the ISO8373 definition:

- **Reprogrammable**: whose programmed motions or auxiliary functions may be changed without physical alterations;
- **Multipurpose**: capable of being adapted to a different application with physical alterations;
- **Physical alterations**: alteration of the mechanical structure or control system except for changes of programming cassettes, ROMs (Read Only Memory);
- **Axis**: direction used to specify the robot motion in a linear or rotary mode.

1.1.4 Major Robot Types by Mechanical Structure

Industrial robot arms and their kinematics can be divided into four major categories:

- Cartesian Robots;
- SCARA (Selective Compliance Assembly Robot Arm);
- Articulated Robots;
- Delta/parallel link Robots.

These four categories are relevant as they each serve to maximize its functionality within its technical capabilities. Although they all comply with the definition of an industrial robot as set by ISO, their individual impacts on market segments, adaptation rate and future prospects differ.

1.1.4.1 Cartesian Robots

As the name describes, Cartesian robots typically move in a Cartesian frame. Cartesian Robots possess 3 main axes, linked in a linear way at right angles. It is Cartesian because it allows x-y-z positioning. Three linear joints provide the three axes of motion and define the x, y and z planes. In some specific cases a 4th axe is added. The Cartesian kinematic solution is highly configurable, given the simplicity of these kinematic, adjusting strokes or lengths and configuration is relatively easy when compared to other robots. Cartesian solutions have numerous applications within the industry. They can be applied to both small and large workspaces. Cartesian robots are typically called upon to serve applications where the gripper or product remains in the same plane. Being the subassembly of individual axis the Cartesian robot can be tailor-made for its job, often working at high speeds. It is the most basic form of an industrial robot, on the bottom scale of the definition. These robots are also called Gantry robots. An example of a Cartesian robot is given in Figure 1.

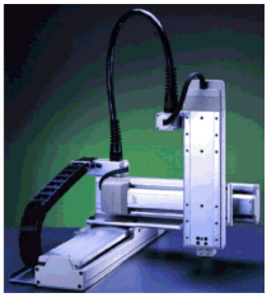


Figure 1. Cartesian robot [1]

Cartesian robots find their main applications in unloading of plastic injection moulding machines and in palletising of boxes. Given their relative easiness of structure and hence need for control, these robots are manufactured not only by some major international manufacturers but also on large scale by many small workshops.

1.1.4.2 SCARA Robots

The SCARA robot is a non-typical 4-axis robot and offers a cylindrical work envelope and this category of robot typically provides higher speeds for picking, placing and handling processes when compared to Cartesian and articulated robotic solutions. They are as termed in industry ‘slightly compliant’ in the XY range but rigid in the Z, hence their name. SCARA robots were developed in 1978, in the laboratory of Professor Hiroshi Makino, at Yamanashi University in Japan and deliver greater repeatability by offering positional capabilities that are superior in many cases than those of articulated arms [1.13]. So where are SCARA robots applied? SCARA robots are usually used for lighter payloads in the sub 10 kg category for applications such as assembly, packaging and material handling. Their main application therefore is Pick and Place. In various industrial processes, SCARA robots are used for high speed and high repeatability handling of cells in smaller workspaces. SCARA robots are similar to the human arm being a jointed two-link arm. That is why they are often found in applications like pick and place, SCARA robots replacing human repetitive work, of course at a much higher speed and precision. As they are relatively small in size, they can be integrated in many machines and production lines; however their use is limited because of their XYZ range, induced by using only 4 axes. Without capabilities of turning its wrist, re-orientation of a product after pick-up is virtually impossible by a SCARA robot. With its cylindrical work envelope, using a 180 degrees pick and place instruction would force the tool center point to move in a circular path, which is not necessarily the shortest path. So the superior speed of SCARA is determinant if they want to stay competitive towards articulated robots. The SCARA robot can be seen in Figure 2.

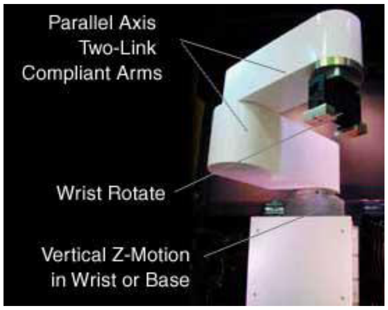


Figure 2. SCARA robot [2]

1.1.4.3 Articulated Robots

Articulated robots differ from Cartesian and SCARA by having a spherical work envelope. Each axis is serial linked with the next one. Industrial articulated robots carry up to 7 axes, all axis serial linked. The majority however of robots in this category is equipped with 6 independent joints, giving it six degrees of freedom. These robot arms offer the greatest level of flexibility due to their serial articulation and increased numbers of degrees of freedom compared to Cartesian and SCARA robots.

A six axis articulated industrial robot allows for an arbitrarily placing of a work piece in space using six parameters; three for the specification of the location (x, y, z) and three for the specification of the orientation (yaw, roll, pitch). Because of this ability it is the largest segment of robots available on the market and therefore offers a very wide range of solutions from tabletops to very large 1,300+ kg solutions. Articulated robots are frequently applied to process intensive applications where they can utilize their full articulation and dexterity for applications such as spot and arc welding, painting, dispensing, loading and unloading, assembly and material handling. Their first usage was in the car industry while in 2012 articulated robots are being applied to a wide variety of applications. The ever-growing output volume in the car industry and the need for cost reduction drove the practical mass use of articulated robots. Big names like GM and Renault had their own divisions for robotics. Each car assembly factory can use up to 1,000 articulated robots whilst having only 5,000 workers, a ratio of 1 to 5! In car factories the main application for these types of robots is spot welding, arc welding and handling of car body and parts. Later more advanced applications like underbody sealing and laser welding were introduced using articulated robots, and more often than not using vision systems.

Articulated robots improve the productivity of these expensive car assembly lines by ensuring that manufacturing operations move at a constant pace with minimal machine idle time. A robot is a mere component of any production line, albeit a highly flexible and reliable one. Hard automation might fulfill a dedicated function, but hard automation comes at a high price: the grouping of various valves, cylinders, sensors, motors and controls come not even close to the reliability of a robot, with up-times of 99.99%! Robots allow for faster and easier set-up when a changeover occurs at the line. And it is not only the big automakers that use robots. Robots have been in factories since 1962 and are a mature technology. Companies with < 500 employees now have the highest robot adoption rate. The second reason why articulated robots can help business is that they deliver for a higher level of the output quality and subsequently lower scrap. Articulated robots provide higher quality and yield because of more controllable, predictable and repeatable process consistencies. Imagine for your production process if you would only have half of the currently rework/scrap costs. Or likewise, what is your current number of customer returns/rejects? Could this be reduces drastically if robots were used? Lessons learned in the automobile industry are now being deployed i.e. in the food industry, from cutting raw meat with robots (increasing the quality of the cut hence a better yield of the price/kg) to handling of salads and fruits (time to market is faster, putting fresher produce on the supermarket's shelves). The 6-axis robot example can be seen in Figure 3.

Figure 3. Example of a 6 axis articulated robot [3]

1.1.4.4 Delta Robots

Delta robots, also known as Parallel Link Robots or spiders, make up the last category of industrial robotics. This kinematic solution provides a conical or cylindrical work envelope. Delta robots are most frequently applied to applications where the product remains in the same plane from pick to place, XYZ. Its design of the arms utilizes a parallelogram and produces three purely translational degrees of freedom driving the requirement to work within the same plane. Base mounted motors and low mass links allow for exceptionally fast accelerations and therefore greater throughput when compared to other robots. Delta robots are characterized by its 4-axis design; 3 parallel arms and one rotational axis at the wrist. The robot is an overhead mounted solution, which maximizes its access and also minimizes its foot print. Delta robots are designed for high-speed handling of lightweight products and offer lower maintenance due to the elimination of cable harnesses and the absence of multiple axes. Parallel robots are deployed into many steps of food-processing lines. They offer high-speed transfer foodstuffs through manufacturer lines and a multitude of processes. Food is categorized in two segments: primary (unpacked) or secondary (packaged). In 2012 delta robots can work both in primary as in secondary sector. The former has more technical constraints with respect to the robot specifications however, as the robot may not contaminate the handled food. Delta type robots are relatively easy to design and manufacture, given the fact that they only drive three motors in parallel, while the fourth axis drives the rotation of the gripper. In 2010 I found more than 40 different manufacturers in the industrial market place. To illustrate the speed of these robots I can mention the Quattro parallel linked Delta robot from Adept Technology, Inc. It achieved 300 cycles per minute, illustrating the capabilities for this class of machine to handle (food) products at high rates. The scheme of the Delta robot can be seen in Figure 4.

Figure 4. Example of a 4-axis delta robot [4]

1.1.5 Robot Economics

With the growing importance of robots in society so did grow their economic impact on its industry. In analyzing the market data on robots one cannot neglect the economic crisis as experienced in 2009. The crises abruptly terminated many trend paths, grow patterns and reshaped the way of financing industries and governments. So in order to make valid statements I recognize the period up to the economic crisis and the period afterwards. Different to military purpose robots, their industrial counterparts are more sensitive to the economic trends. This is clearly to be seen over the last 3 to 5 years. The troublesome year of 2009 saw a worldwide economic and financial crisis (it started late 2008) and caused substantial decreases in industrial output worldwide, also saw a significant slump in the sales of industrial robots. If volume figures are to be compared with 2008, which many considered one of the most successful years, 2009 showed a decline of close to 50% (in absolute terms 60,000 units). Since 1994 this level has not been seen before. Robot installations had never decreased so heavily.

The relevance of the robotics industry becomes clear when assessing its economic numbers. Although many indicators can be assumed, the most relevant data is the stock of robots. The robot stock indicates the number of robots installed in factories and sites worldwide. Considering units, it is estimated that the worldwide stock of operational industrial robots will increase from about 1,020,700 units at the end of 2009 to 1,119,800 at the end of 2013 [1.14]. The crisis hit most western economies, and subsequent investment in production lines and capital goods. The monetary value of the industrial robot market decreased end 2009 to a sill staggering figure of $3.8 billion. This amount cited above does not include the cost of software, peripherals and systems engineering. Hence the actual robotic systems market value will be about two to three times as large. The world market for robot systems in 2009 is therefore estimated to be $12 billion.

Considering a market of $ 12 billion in 2009, a subsequent split over the various application segments is as follows:

- Material Joining (Arc welding, Spot welding, Laser joining, Gluing) 45%;
- Material Handling (Load/Unload, Pick & Place, packing and palletizing) 50%;
- Painting (Painting and Sealing) 5%.

A strong recovery of worldwide robot installations in 2010 will result in an increase of about 27% to about 76,000 units. The main impulses are coming from China, the Republic of Korea and other South-east Asian countries. But the robot supplies to Japan and North America will also substantially increase. In Japan robot sales were decreasing since 2006. In North America sales already declined in 2008. In Europe, the recovery has a slow pace and is mostly based on the exports. The domestic demand is still weak although major investments in capacities and modernization took place between 2005 and 2008. Robot sales continuously increased between 2005 and 2008. The main driver of the recovery is the automotive industry, which has restarted to invest in new technologies, further capacities and renovation of production sites. Base business or general industry – which contains all other industries, except automotive - already increased its robot investments between 2005 and 2008. This will continue between 2010 and 2013.

1.2 Robots used for Military Purposes

The birth, growth and adaption of industrial robots have followed some logical steps. Since the 1970s robots have made a dramatic inroad in our factories and in 2012 robots are used in the automotive industry, electronics manufacturing, food and beverage, metal and general industries. As understood in the previous paragraph there are more than 1 million robots in total in operation. So how does this compare to military robots? Did they evolve in a similar path as their industrial cousins? And what's more important, will they evolve in the future the same way? To assess the market situation of military robots I approach the problem from a similar point. I assume an historical overview, a defined segmentation and an economic approach to verify its current status. Looking at the available data sources at hand, the first observation I can make is that the field of Military Robotics is still in its early growth phase. In example, as of October 2008, coalition UAS (unmanned aircraft systems) also known as Unmanned Aircraft Vehicle have flown almost 500,000 flight hours in support in Iraq and Afghanistan. According to the US Department of Defense Roadmap 2009-2034 [1.15], UGV's (Unmanned Ground Vehicles) have conducted over 30,000 missions, detecting and/or neutralizing over 15,000 IEDs (improvised explosive devices) and UMS (unmanned maritime systems) have provided security to ports. Less than 10 years ago there were hardly any drones or unmanned vehicles in active duty. So in a decade these military robots have seen a tremendous growth. Industrial robots adaptation rate grew since the '70s into the millennium. The military robot's adaption rate is certainly faster. As with all new technologies, they bring new opportunities, challenge long traditions and open new debates. The future use of these robots needs to incorporate the various challenges that are brought by battlefield and conditions as per this decade. In [1.16] Szabolcsi determined main characteristics and requirements of the UAV systems used for firefighter applications. Article of Szabolcsi dealing with flying and handling qualities of the UAVs applied for police purposes and he derived complex set of the characteristics needed for preliminary design of the UAV automatic flight control system [1.17].

A clear understanding, like with industrial robots, is compulsory to limit the scope of the thesis. For the analysis on industrial robots I used the ISO definition of a robot as a machine that can automatically execute tasks, based on programs: a fixed or mobile device, to be used in industry having at least three axes. No such definition exists when it comes to military robots. In fact, there is no international board or instance governing the standardization or production of military robots. So then what is, or what defines an autonomous military device as a military robot? For example, an intelligent landmine can work autonomous and follows a certain pre-determined programming, but I do not consider these deadly devices as military robots. In order to make valid statements on the research aims I first review the brief history of military robots. Next I examine the various uses of military robots. In analogy to industrial robots, the application objective determines design and functionality. Hence a starting point to understand the current status of military robots in force. I proposed the Military Robotics Driver Matrix to make an analysis on the types, use based on the objectives of military robots.

1.2.1 History of Military Robotics

In order to understand the future of military robotics it serves to understand its roots, its history. Although the use of tools to gain a competitive advantage is as old as human kind, for research purposes I concentrate on the use of flexible automation in the battlefield. Robotics itself is a recent science; industrial robots only exist since the 1970s.

However due to the development of CPU processing technology, digital technologies and mechatronics, the military versions were quick to emerge. Albeit the many (theoretical) applications were already quite early recognized by human kind. Around 1500 AD it was the great Leonardo da Vinci, in his engineering role, who invented many (military) machines and mechanical devices like planes, helicopters and tanks that have become reality only several hundreds of years later [1.18].

The mechanical and electrical engineer Nikola Tesla (1856), inventor of the induction motor, has contributed highly to the development of radar and remote control of vessels. Tesla described as early as 1897 about radio controlled boats and torpedoes in what he called “teleautomaton”. With his close ties to the US military and US electrical industry, his ideas and inventions laid the groundwork for torpedo and UAV’s alike. According to Tesla, these automata were the first steps towards an evolution in the art of teleautomatics. He stated that the next logical improvement was the application of control, beyond the limit of vision and at great distance from the center of control [1.19], putting humans far away from danger. He could not have been closer to the actual reality when it comes to military robots.

In World War II the Nazi’s used their engineering skills to gain battlefield advantage. They developed a range of new weapons and systems, among which were the first (unguided) missiles V1 and V2 and jet propelled air fighters. In the automation field the Nazi’s developed the robotic-like antitank weapon “Goliath” (see Figure 5). These weapons were remote controlled attack vehicles, or tracked mines. They were the first battlefield automation robotic weapons.

Powered by a gasoline engine and Bosch electric motors, the Goliath was equipped with caterpillar tracks to move over rough terrain. According to Jaugitz [1.20] these robotic mines could be remotely maneuvered under enemy tanks and deliver a 100 kg explosive. The Goliath robotic approach allowed the German infantry to stay effectively out of harm's way while delivering deadly charges to enemy tanks and positions.

The German idea caught on and the Second World War also saw the deployment of large size remote radio controlled tanks, developed by the Soviets. These "teletanks" were wirelessly remote controlled unmanned tanks. They were fitted with flamethrowers, smoke canisters and machine guns, and could drop explosive charges [1.21].

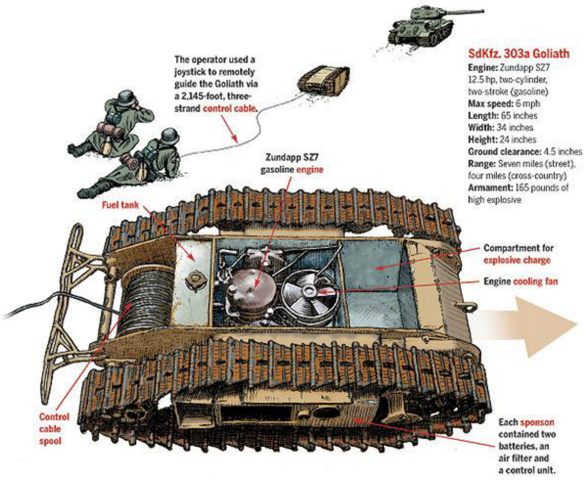


Figure 5. Nazi tracked mine robot "Goliath" [5]

1.2.2 Purposes of Military Robotics

The above-mentioned historical examples show that one of the main drivers for the Nazi's and Soviets to develop their robotic like tanks and weapons was to keep human soldiers out of harm's way. Avoiding loss of human live or minimizing injuries - while destroying enemy's personnel and/or hardware - leads to a higher combat advantage, a lower cost of warfare and a higher morale.

Imagining an army completely made up of robots it would see no casualties or 'killed in action' other than destroyed machines. If the ultimate goal of a military conflict were winning it (or not losing it) then the sub-goal would be to do so at a minimum cost to human lives and at a minimum economic expense.

This point clearly distinguishes the industrial robots from the military robots, and is crucial in this research. The former has mere economical targets, being the maximization of profitability, while the military robots have a whole range of objectives. While in 2012 a full ‘robotic army’ is still far off, present day robotics for military do provide an added value to the combat soldiers and war theatre. In principle the use of military robots has the following advantages in war theatre, among others:

- No loss of human live. Humans would be replaced by machines for military tasks deemed too dangerous for humans;
- Effectively removing humans from direct hazardous theatre;
- Reduce possible injuries or “Casualty Aversion”;
- Subsequent effect of casualty aversion is reducing/eliminating the need for casevac and further medical intervention and subsequent lengthy revalidation;
- High level of delivery accuracy by robots (they don’t get tired or stressed);
- Robotics do not experience “fear” or morale issues and can hence be more effective in combat;
- Overall effectiveness due to use of technological skills versus human skills;
- Less or no extensive training needed;
- Less dependence on (re) supplies (robots do not need food, warmth, oxygen or sleep);
- Maintaining home support for operations (A “killed” robot is not a bother);
- Improve battlefield intelligence;
- Increase battlefield communication speeds;
- Higher adaptive rate to terrain and conditions;
- Resistance to NBC (Nuclear, Biological and Chemical) conditions;
- Mere economics, value for money, expendability.

Apart from their R&D and production costs, I argue that the cost to maintain robots are relatively smaller than to train, maintain, deploy and shelter human soldiers. This shows that military robotics in its optimum form would be highly beneficial. In its theoretical application these advantages cannot be neglected by any state. With such clear benefits the adaptation by military of these existing and future robotic systems is to be expected.

1.2.3 Military Robotics Driver Matrix

So far no segmentation of military robots is available. The current collection of military devices that can be considered robots is too sizeable to be treated as one group. Subsets of military robots with common applications and goals are relevant to be treated as such. For industrial robots different subsets exist based on their form and application, respectively:

- Cartesian;
- Articulated;
- SCARA;
- Delta robots;

and

- Material Joining (Arc welding, Spot welding, Laser joining, Gluing);
- Material Handling (Load/Unload, Pick & Place, packing and palletizing);
- Painting (Painting and Sealing).

While it is clear that this segmentation is aimed for industrial use, it shows the fundamentals behind it. What is relevant is the application the robot was designed for. Analyzing the list of goals identified in 1.2.2 it is possible to derive two main drivers where military robots are concerned. Military robots have two main objectives; cost down and keeping humans out of harm’s way. Hence on one side I adopt the impact the deployed military robot has on the “human” aspect, the indefinable but very existing cost of life. On the other side the deployment of military robots can be arranged on a more economical or cost saving scale. In other words two axes: Human Impact and an Economic Impact. Using these two objectives it is now possible to group military robots into segments and types according to their impact on the two identified scales. The combination of these two main driving factors and scaling provides the “Military Robotics Driver Matrix” as shown in Figure 6a.

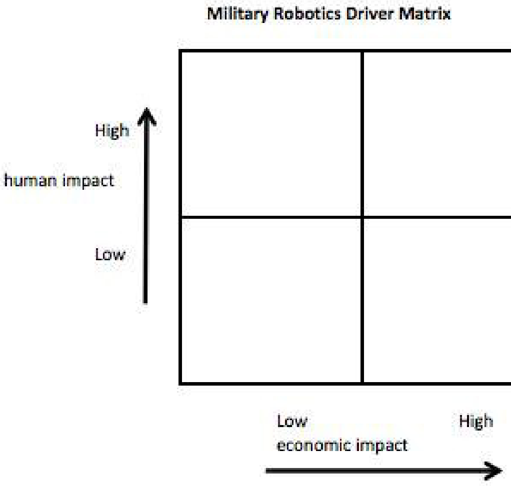


Figure 6a. Military Robotics Driver Matrix [6a]

The axes are scalable, the impact a military robot has on the human property can be classified as *High* if it can save human lives (or limbs for that matter...). A small backpack model reconnaissance plane that shoots images from the battlefield serves a great purpose but doesn't safe a human life in the direct sense by the deployment of the robot. Here the human impact can be considered *Low*. A similar scaling takes place on the economic axe. The two axes are also not mutually exclusive but complement each other depending on the military application of the robot. In other words, robots with a clear military purpose aim to either pursue an economic objective, a humanistic objective or a given scaled combination of the two factors.

Military robots come in all sorts of shapes, size and application, but all fall within each of the four quadrants. Some robots combine some or all segments. The given analysis does not aim to determine the Battle Effectiveness of each of the robots, which can be identified within these four segments. Battle Effectiveness itself can be considered a sub-objective of the Economic Impact. Poor use leads to poor results. Instead, the Military Robotics Driver Matrix aims to understand the driving forces of the various military robots, and to derive a useful segmentation from it, not its mere military effectiveness.

Below in Figure 6b, I classified the four quadrants of the Military Robotics Matrix according to the four derived segments:

- Reconnaissance Robots
- Prevention Robots
- Logistics Robots
- Assault Robots

For each a comprehensive segmentation explanation will be given supported by an actual example of military robots.

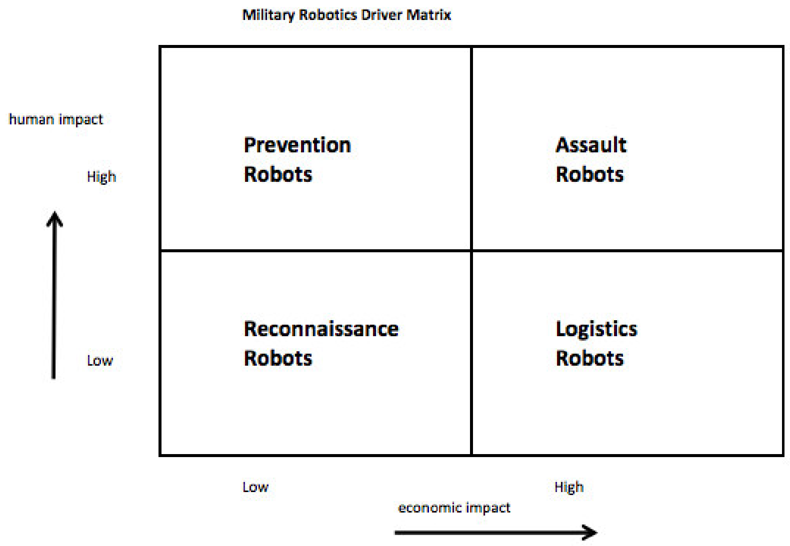


Figure 6b. Military Robotics Driver Matrix [6b]

1.2.3.1 Reconnaissance Robots

Battlefield automation with a low impact on the human side, and a low economical gain can be labeled as *Reconnaissance Robots*. Autonomous battlefield sensors that report theatre intelligence on troop movements, presence etc. can be named in this respect. The segment Reconnaissance Robots distinguishes itself by the passive nature of the robots in question. These robots are designed to gather intelligence, by means of sensors and /or vision systems. They do not actively deliver ordinance. Neither do they have a large impact on the human side, nor the economic side. Although important from a military standpoint the main purpose of the wide range of reconnaissance robots is to provide remote intelligence. The Dragon Runner robot – used widely in Iraq by US forces - is a good example of a robot in this segment. These robots are designed to carry in a bag pack by Marines and infantry troop. A recce robot can be seen in Figure 7.

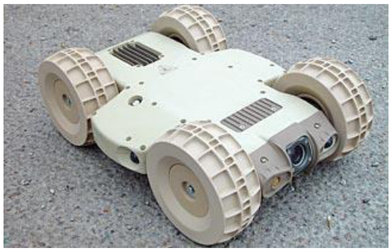


Figure 7. Dragon Runner, Reconnaissance War-Bot [7]

All terrain reconnaissance robots are used in various urban terrain operations. All terrain reconnaissance robots have a rugged design and are equipped with one or more digital cameras so they can relay images of operational theatre back to units operating from a safe place. These robots can be tossed around, climb stairs, dropped from cars, move in and out of houses and bunkers. In addition these robots can move through tunnels with water, scan for snipers, search buildings, screen people for traces of explosives etc. Characteristic is the relatively easy and cheap manufacturing process and their ease to use. Their air equivalent is to be found in the form of small UAV planes. These are remote controlled planes that can fly at low altitude over terrain to gather and send images. The concept of planes has to be taken widely as they can take the form of fixed wing planes but also quad rotor and or helicopter versions exist.

1.2.3.2 Logistics Robots

Going up the scale of the economic impact on the Military Robotics Driver Matrix leads to the *Logistics Robots* quadrant. The Logistics Robotics segment discriminates itself from mere reconnaissance tasks through the larger economic effects realized while keeping the impact on human objectives low. Unmanned cargo helicopters like the K-Max [1.22], developed by Lockheed Martin and Kaman Aerospace, to (re) supply outposts in dangerous or difficult penetrable terrain can be named in this effect.

Also the various MULE robots are a typical example of military applications of Logistics Robots. The ‘BigDog’ robot by Boston Dynamics features a 4-legged animal like mechanical design, able to carry approx. 170 kg of payload. According to its manufacturer Boston Dynamics, BigDog’s control system keeps it balanced, navigates, and regulates its energetics as conditions vary. The robot has various sensors like joint position, joint force, ground contact, ground load, a gyroscope, LIDAR (Laser Detection Imaging and Ranging) and a stereovision system. Other sensors focus on the internal state of BigDog, monitoring the hydraulic pressure, oil temperature, engine functions, battery charge and others [1.23].

Logistics robots equivalents can be found manifold in general industry where robots manage heavy payloads to relieve human workers. The benefit works in two ways because these robots can supply more cargo like ammunition and food to the various hot spots relieving the human soldiers from transporting this load, in turn making them in theory more effective (less fatigue, higher level of concentration). The supply of troops in general is a dangerous operation due to the various ambush opportunities as supply troop typically moves slower than combat troop. The Logistics Robot carries a relative high economic impact as the effect of bulk transport without use of human intervention implies less human expenditure and exposure. Neither driver nor pilots are necessary. Also that implies less or no need for protection or lifesaving equipment of the excluded humans so lighter, flexible vehicles with larger range of autonomy.

Figure 8. 'Big Dog' by Boston Dynamics. Logistics robot [8]

1.2.3.3 Prevention robots

An area that has been under investigation for many years by many states is that of minesweeping. *Prevention Robots* contain the large group of de-mining robots; IED removal and similar robots to be mentioned here. Demining work done by a human or by a robot makes a difference in case an unwanted explosion occur. The effect on humans, in case of bad outcome while demining, is often a life or death equation, according to Davor et al [1.24]. The Military Robotics Driver Matrix identifies this as the *Prevention Robots* segment.

This group of robots contains robot automation typically designed to keep humans out of harm's way while the economic impact of these robots is minimal. It does not have a high impact on war as a total, nor does it have large economic impacts. So casualty aversion is the main objective. The implied human costs are high. Injuries are often grotesque and need extensive revalidation. Its impact on society is large as soldiers come back from the battlefield dead or mutilated for life. Military Prevention Robots also are used in civilian life.

After a war, a 100% de-mining effort is executed to minimize the effect of leftover mines on the civilian population, using the before mentioned de-mining or prevention robots. De-mining robots have been around for many years, and due to their technical simplicity are being built by countries worldwide. In 2012 these robots are fully or semi-autonomous in detection and defusing of mines, IED etc.

Figure 9. 'De-mining' robot deployed Prevention robot [9]

1.2.3.4 Assault robots

Within the Military Robotics Driver Matrix the *Assault Robots* are the top notch, most visible group of the matrix. These robots combine maximum impact on (saving) human life while maximizing the economic benefits of using robots for the designed operational task. The whole range of UAV covers this segment. Although the early UAV's were mere drones or radio remote controlled aerial vehicles by human operators, the latest generations UAV include built-in guidance and control systems and advanced vision and weaponry systems. Its role in fighting international terrorism in countries like Afghanistan, Yemen etc. have not gone unnoticed, only in 2007 alone 2.2 billion US$ was invested in these unmanned systems world-wide [1.25]. To fly a UAV requires far less training than a real fighter pilot and is riskless for the operator. The UAV may fly over hostile terrain in Afghanistan while its operator works out of an air force base in Las Vegas. As Heath states in [1.26], operating a UAV reduces manpower. In addition the operational cost of flying manned fighter jets in war theatre versus unmanned is much higher. When a UAV gets shot down, there is a certain risk of loss of technology ownership. When a fighter gets downed there is the additional impact of capture of its pilots who ends up as a prisoner of war. So from both a human and an economic viewpoint the rewards to employ assault robots are high.

Not only UAVs are found in this quadrant. Land and sea based systems exist as well. Robotic battle tanks, like the before mentioned Goliath example, are to be found in the Assault Robot segment. These infantry robots are designed to keep human soldiers out of harm’s way while being on the forefront of the battle. Assault robots or ARV (Armed Robotic Vehicles) are designed to overcome human limitations like fear, exhaustion, and exposure to climate, terrain and battlefield conditions, while maximizing their lethal potential. These ARV can be made part of an organization of vehicles and sensors. Equipped with C2 (Control & Command) software /hardware and various communications systems. They have semi-autonomous navigation and mission equipment operations. Fire authorization is handled via C4ISR (Command Control Communications Computers Intelligence Surveillance and Reconnaissance) network where humans are in control [1.27].

Figure 10. Predator UAV firing a Hellfire missile. Assault robot [10]

Assault robots one-step further in time implies ending up with the robots shown in Hollywood movies, the all-purpose autonomous fighting machines.

These four segments can eventually be further sub-segmented into land/sea/air robots but it doesn't offer a different function or benefit. The growth and use of robotics in the military is an irreversible trend. The adaption rate for Assault robots like UAV is high, as they have proven their value in the last decade. In [1.28] Szabolcsi derives theoretical backgrounds for preliminary optimal design of the UAV automatic flight control systems. Szabolcsi in [1.29] deals with flight path design of the UAV systems built by extra-cheap concept. According to Newsweek more than 40 countries are developing their own UAV [1.30]. The success of UAV is so high that other interest groups are adopting these technologies as well. In the US certain Police departments are experimenting with drones for surveillance while in the US the spy agency CIA (Central Intelligence Agency) is said to operate their own drones, disconnected from the military. One can only speculate their tasks, apart from the obvious surveillance. Usage of ground operated unmanned assault robots are still low due to the technical constraints. The opposite is true for Reconnaissance and Protection Robots. These two groups enjoy wide interest. Their technical threshold level is low while output is high.

1.3 Conclusions

From the historical analysis of automation I conclude that automation, both for industrial robots and military robots have common historical roots. They stem from the human desire to control its environment and to control output by using of mechanical devices while reducing the burden on humans. Both serve a higher economical objective, where industrial robots aim to reduce direct manufacturing costs the military robots aim to keep humans out of harms way and to reduce the economic impacts of warfare. Industrial robots have evolved in 4 major types: Cartesian, SCARA, articulated (serial link) and delta robots (parallel link). Each of these types fit current industrial market conditions and develop with technology in new generations. The market for industrial robots with 12 billion US$ is large. I conclude that industrial robots are in 2012 a key component of industrial automation. Military robots use similar technology as industrial robots. The wide spread use of military robots came 35 to 40 years later than the industrial robot, which were developed in the '60s. The broad variety of robots used by the military combined with the various objectives signifies the still early stages of these robots. The public focus and discussion handles mainly around assault robots, following the successes of UAV in the gulf war and the war on terror in Iraq and Afghanistan. UAV's are being developed by most industrialized and military powers around the globe. Depending on their impact on human cost and or impact on an economic benefit all military robots can be classified as: logistics robot, reconnaissance robot, prevention robot and assault robots. Military prevention robots have a larger history coming from the de-mining area and find attention in academic circles. The logistic and reconnaissance robots are becoming a new growing segment.

CHAPTER II: ECONOMY AND ROBOTS

In this chapter I will investigate whether a complete new design of industrial robots can be expected. To establish this I need to proof whether from an economical point of view it is feasible. For this I investigate the industrial robot market, market densities and I will review the aging problems within society. In addition I will analyze the impact that robotics has as an industry on the labor markets. Acceptance factors of robots are included. Literature on flexible automation does not provide any modeling on the adaptation rate by industrial robots within companies. This is relevant to understand the penetration of robotics within industry. In chapter 2.2 I will demonstrate a workable model for the growth phases of robots within industry.

2.1 Economics of the past Era

To better understand the economic impact of robots over the last 40 years, I first look at the position of industrial robots as a group on the PLC (Product Life Cycle). Although the Product Life Cycle is a hypothetical approach, it serves to provide a good indication of what may happen in the future. A theoretical PLC is given in Figure 11.

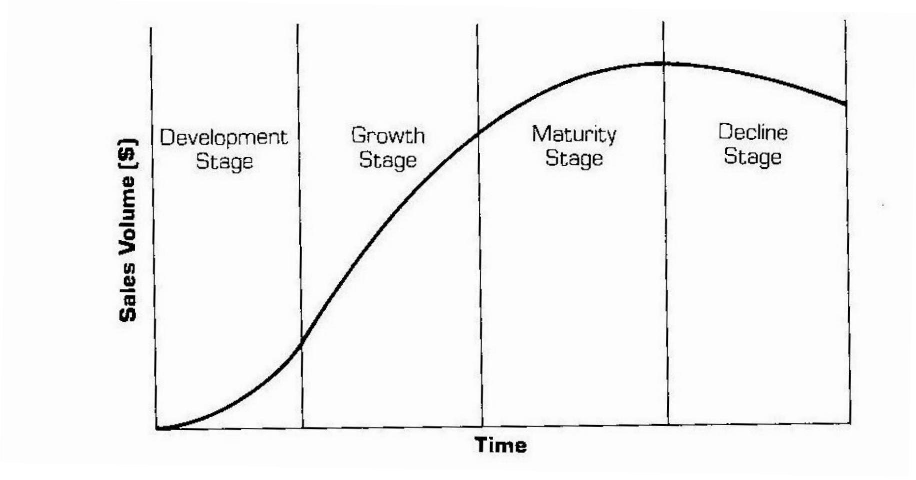


Figure 11. Theoretical Product Life Cycle [11]

The Product Life Cycle concept combines the sales volume over time and assumes the stages of the life of a product/technology [2.1]. Where the start takes a long time for a product to become accepted, it is followed by a steady growth till it reaches adulthood and eventually fades out due to new technological solutions. Or if I speak in human terms: birth, growth, maturity, decline and death [2.2]. In the early stages of the cycle, new products need high advertising and promotional expenditures, while later when these needs decline due to a decline in need of information prices typically fall and competition becomes fierce. The cycles of similar technological products like for instance typewriters, gramophone players, video recorders all followed similar paths like displayed in Figure 11.

2.1.1 PLC for industrial robots

When I assemble the sales data obtained by the International Federation of Robotics or IFR [2.3], I can construct a graph of the PLC for industrial robots since their conception in the mid ‘50s till the year 2009. This PLC for industrial robots is displayed in Figure 12. It is clear that the real PLC for industrial robots – or any other product for that matter - does not follow exactly the bell shape of the theoretical model given in Figure 11.

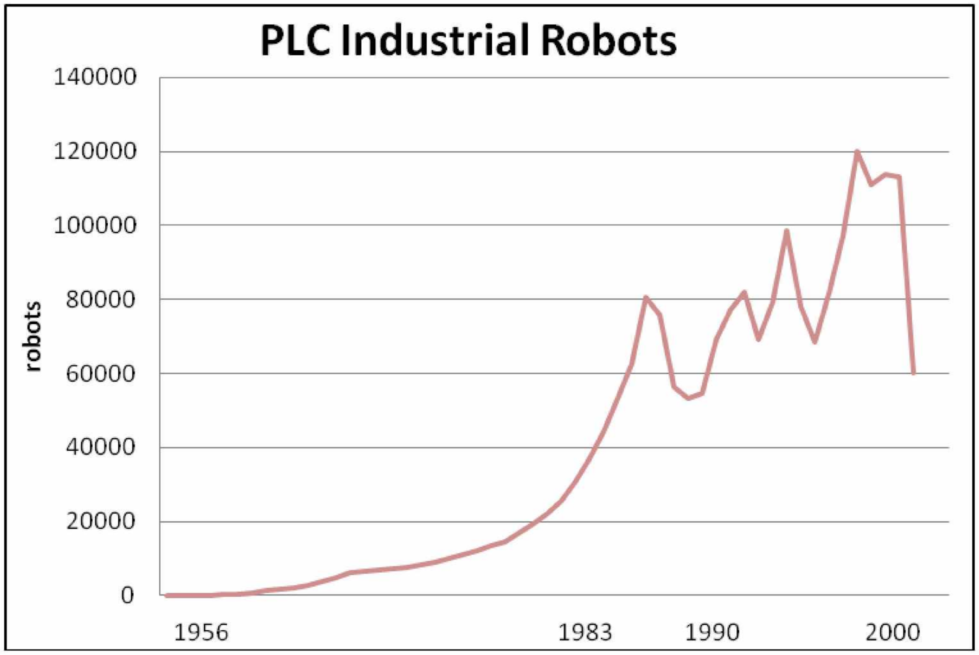


Figure 12. Estimated Product life Cycle based on IFR data [12]

I consider that industrial robots are to be found growing steadily, well in the Maturity phase, while i.e. service robots are still in their development stage. It is predicted that after economic crisis the volume of industrial robots will continue to grow [2.4]. So the decline in sales volume due to the crisis does not conclude a decline in the life of robots. Hence the sharp drop at the end of the graph is a result of the financial crisis of 2008 and its impact on 2009 sales numbers. The drop is directly related to this crisis.

The adoption rate of robots in industry will grow and the need for skilled labor in the industrialized countries is evident. If the position of industrial robots is entering in its maturity phase, it supports the fact that industrial robots are being transformed into a commodity. Economies of scale dictate high barriers to entry for new comers into the industry. Prices of robots will continue to go downward based on their position in the PLC, again economies of scale being the force to cut product unit cost. I conclude from the Product Life Cycle model that industrial robots up to the crisis followed a normal path, they went through the stages of Development (Engelberger), Growth Phase (early adaption by the automobile manufacturers) and they are now experiencing further growth, entering in the Maturity Stage.

What is true for industrial robots is not necessarily true for other classes of robots, especially robots for military applications. Military robots in general are in still in their development stage of the PLC. Exceptions are the UAVs. UAV’s are experiencing a strong growth after a wide deployment in the gulf wars, the Afghanistan theatre and the war on terror fought world-wide in areas like Yemen, Somalia and Pakistan. Built as a reconnaissance plane UAV’s can now be fitted with anti-armor missiles and are used widely as an attack/deterrent weapon and for C3 (Command Control Communications) missions. UAV’s flew over 300 combat missions during Operation Desert Shield/Storm. Currently there are more than 328 Army UAV deployed in theater, summing a total of more than one million hours of flight. The US Army will train 2,100 operators in fiscal year 2012, a staggering 800% increase compared to 2003 [2.5]. This data is typically in line with the early Growth Stage within the Product Life Cycle. Extensive growth can be expected over the coming 20 years as shows the industrial robot PLC example.

2.1.2 Concentration Curve Analysis

While the early manufacturers of robots were linked to the car manufacturers, in 2008 some 40+ manufacturers were active in the production of articulated, Cartesian and SCARA robots. Starting 2007 a strong growth is noticed in new manufacturers of Delta type robots. This is an important point I need to mention, as there has been an enormous leap growth of delta robots since 2007. What started as an academic research product, these robots were first introduced in the market by ABB, called Flexpicker.

The exclusive patent rights ended in the new millennium. Due to its relative easy drive and motion control structure starting years 2005-2007 many local manufacturers of 3 or 4 armed delta robots could be found in Europe and USA. In Europe alone in 2005 some 500 units were sold, only to grow to more than 4,000 in only 3 years [2.6]. In 2008 a total of some 40+ manufacturers can be identified, selling more than 100,000 industrial robots in total. A measure to better understand the current market position of industrial robots is the degree of concentration. In the Concentration Curve I measured the cumulative turnover or market performance versus the number of suppliers.

Figure 13 shows the graph as calculated for 2008 supplier's market data. The diagonal line would indicate a complete absence of any concentration; all suppliers would have equal share of the market. The concentration curve shows the influence of the various suppliers. The Concentration Curve as shown in Figure 13 displays a clear high degree of market concentration. Few leaders dominate the market. In fact, the first 4 producers (FANUC, Yaskawa, Kuka and ABB) of industrial robot arms make up close to 65% of the total market. This is yet another clear sign that the market for industrial robots is coming to maturity in 2008. With high concentration the "barriers to entry" are also getting very high, it is difficult for newcomers (i.e. China has no robot manufacturing capability in 2012) to enter due to the large market positions of the leaders. Leaders compete on price by their economies of scale

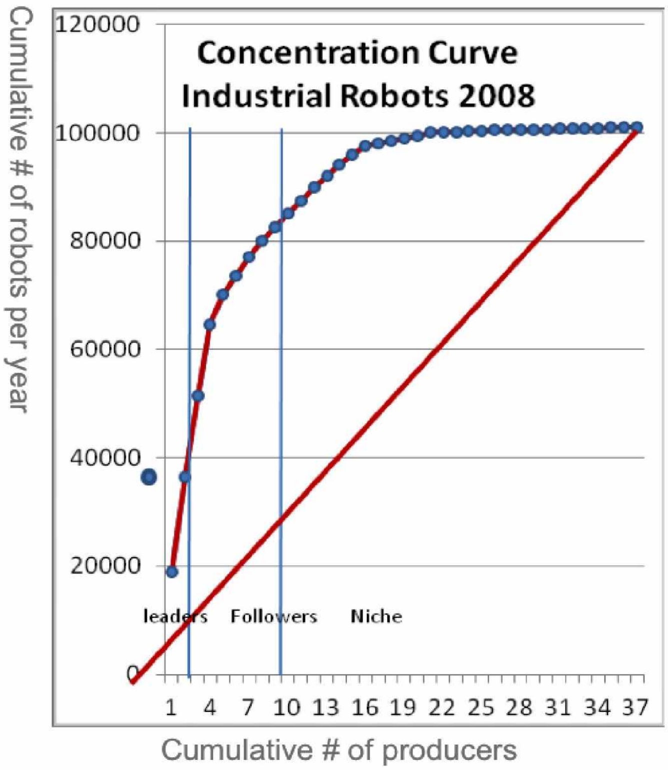


Figure 13. Concentration curve - Industrial robots 2008 **[13]**

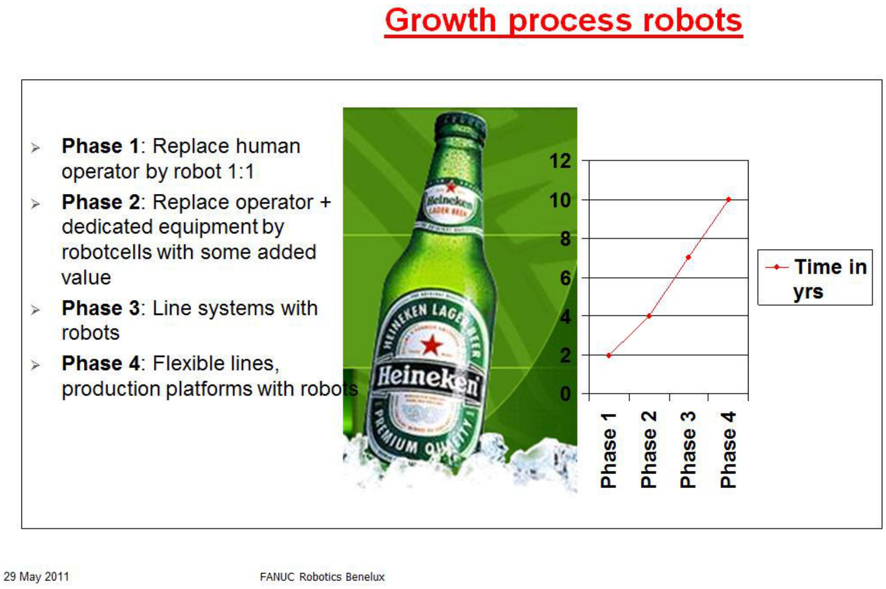
New comers or smaller producers – followers – have only chance of survival if they focus on niche markets. In these niches a relative higher margin can be achieved due to the added value or specific function offered. This is the case of the various small sized manufacturers of Delta robots. A concentrated market has also the typical inclination to increase the concentration going to high levels of concentration; small players are being swallowed-up by larger players. This can have far reaching consequences for the industry and its actors.

2.2 Economics of the New Era

If the automotive industry, as an early adapter of robots in the PLC is the role model, then what is the underlying growth theory of adaptation of robots by the industry? How do robot and their use evolve? For this I made a new conceptual framework based on an analysis I provided at an internal congress on industrial automation organized by the well-known Dutch beer brewer Heineken to come up with a framework. Hence I named this framework as the “Robotics Growth Phases” model.

2.2.1 Growth Process of Robots – Adaption by Industry

This model, see Figure 14, describes the adaption rate of robots in industry, whether it being the beverage industry, food industry, medical, plastics, metal etc. The adaption rate of robots by industry is typically following 4 phases: in the first phase a factory starts with robots, where a robot replaces a worker handling a machine. Or, also where simply a one-to-one exchange of humans by robots is realized. The benefits are present but not large. The company gains its first experience with the new high technology and tastes the possibilities of flexible automation. It has to be said that more often than not high barriers had to be overcome to get the robot accepted, hence the typical starting point at t=2 years. The amount of robots in phase one is typically small from 1 to 3 units maximum. The first phase is all about opening up to technology and flexible automation as a driving force of the production platform. Economic benefits are quantified in labor cost saving mainly. Return on investment, depending on many factors, is typically benchmarked at a maximum of 2 years. In the second phase, when time has passed and barriers to the new technology have been reduced and benefits – direct labor saving and increased production rate – are becoming more obvious more operators are being replaced by robots. Also the robots start to do more complex tasks than the operator did, in example the measuring of the output quality. Up to the economic crisis of 2008 most companies using industrial robots (articulated, Cartesian and/or delta) were – and still are – positioned in phase 2.



Growth process robots

- **Phase 1**: Replace human operator by robot 1:1
- **Phase 2**: Replace operator + dedicated equipment by robotcells with some added value
- **Phase 3**: Line systems with robots
- **Phase 4**: Flexible lines, production platforms with robots

29 May 2011

FANUC Robotics Benelux

Figure 14. Robotics Growth Process [14]

Often management decides for copying the success of the first flexible automation solution to multiple production lines, taking benefit of the economic advantages this phase brings, but holding short of the threshold of phase 3.

The next step, or third phase is characterized by a well-accepted time frame of wide spread use of flexible automation using robots in production lines – the automotive role model. Robots typically handle products in its various sub-stages till finished product and packing and palletizing. The early adopters of flexible automation reach the third level. Most western and Japanese car manufacturers operate in 2012 in phase 3. In addition the beverage industry, due to its large volume and uniformity of its products are situated in this phase. Manufacturers of beers/soda's like Heineken and Coca Cola use their financial strengths to have their breweries and plants automated, with robots, from filling to packing and palletizing.

The last phase (number 4) is the ultimate phase: the highest level of flexible automation reachable. The line production with robots are replaced by flexible lines, or island production where the manufacturing process of the product (beer, a television, a robot, anything really) is handled by various disconnected production groups of robots, producing to intermediate production warehouses. The disconnection of lines implies getting rid of the negative aspect of line production whilst maximizing the benefits of flexible automation, maximizing throughput and maximizing product quality while minimizing cost. The factories of FANUC Corp is a good example, as the world's largest robot manufacturer, FANUC has more than 1500 robots employed, while having only approx. 300 factory workers to maintain its production platforms. With a robot/worker ratio of 5:1, it shows an enormous high degree of automation.

Food industry can be characterized as being in phase 2. Solar industry and pharmaceutical industry are still in phase 1. Some automotive factories are moving into phase 4. Many metal transforming factories have been using arc-welding robots – a typical phase 1 operation. Now they too are trying to move into phase 2 by automation of press brake tending, laser welding with robots. The conclusion from this modeling is that most companies, and even the development of economies, follow the growth pattern of the "Heineken Growth Phases" – model. It is the underlying process of industrial automation and can be used to establish current position of companies/sectors and predict future steps and investments necessary. The model can guide management in determining the type of staff, education levels and required inputs and expected outputs of the various stages of flexible automation.

2.2.2 Economic Impact of Robotics

The PLC example showed that the number of installed robots, with an average lifetime span of 15 years, is growing. To understand the impact on a national scale however, the absolute numbers have to be seen in a relative approach. In example, in an under-developed country even a relative small number of installed robots results in a high degree of automation. Phase 1 of the Growth model explains the substitution of workers by robot. To better understand the economic impact of robotics I used the robot density. The density is calculated by matching the number of robots with the number of workers employed (per 10,000) in manufacturing industry. Figure 15 shows the density chart of industrial robots per industrial sector.

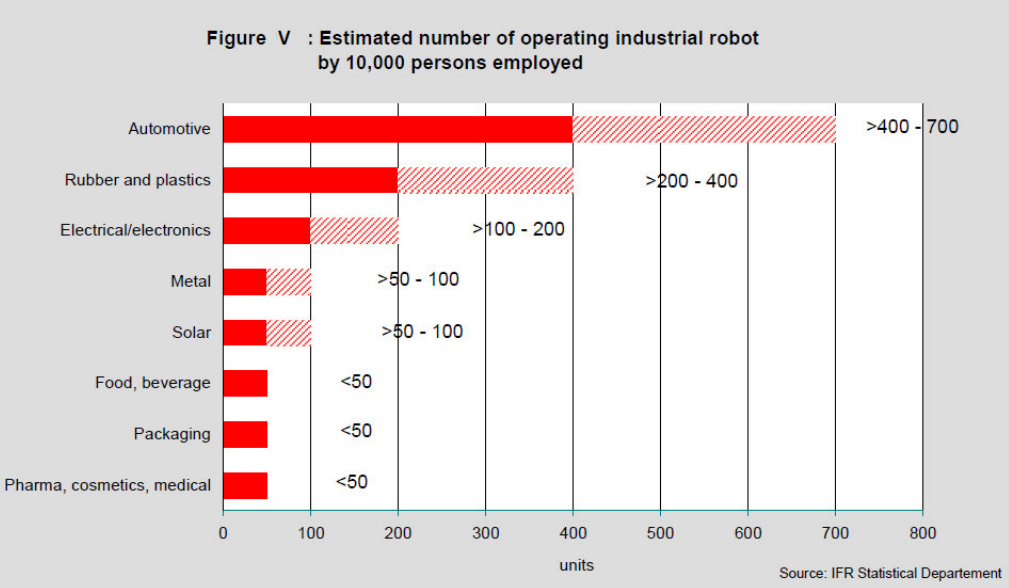


Figure 15. Robot density per industrial sector [15]

It comes as no surprise that the automotive sector has worldwide the highest density in 2009, ranging up to 400 robots per 10,000 workers. Other traditional sectors like Food and Beverage are still on the low range of robot density, but with large potential. New sectors like Solar Panel manufacturing is emerging.

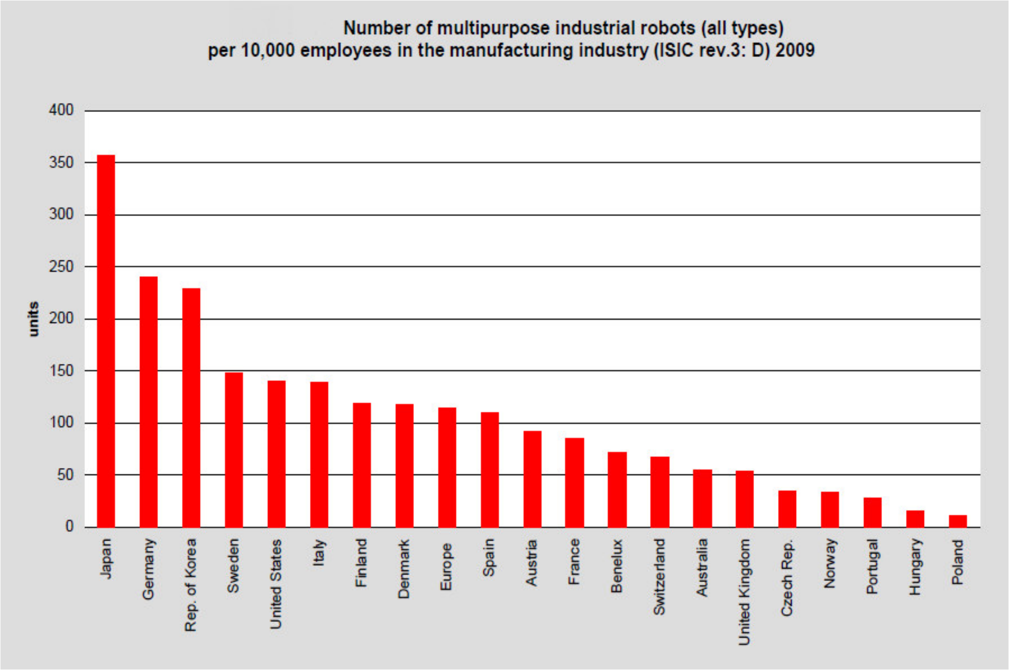


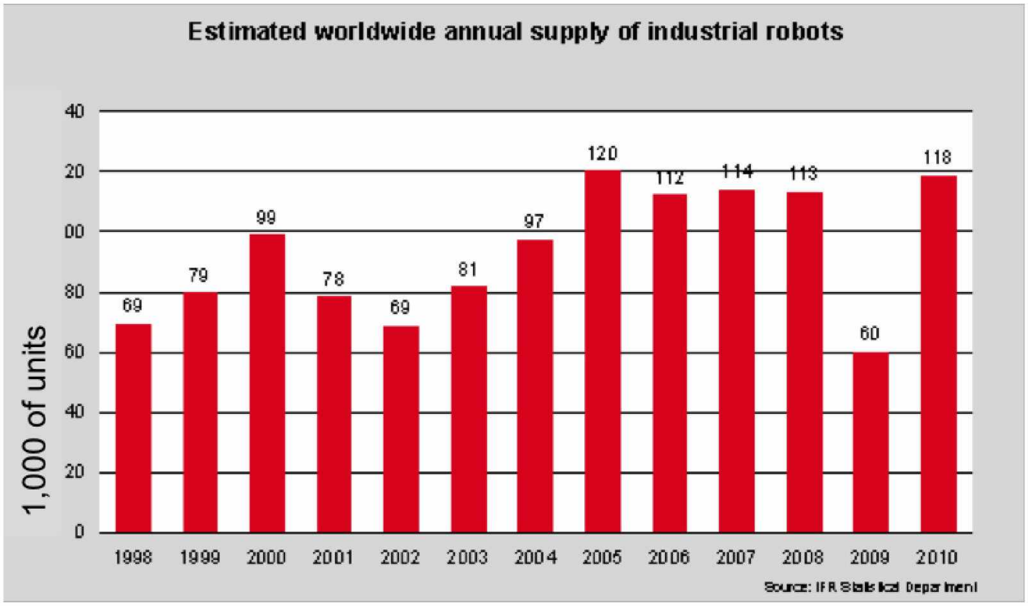
Figure 16. Robot density per country **[16]**

According to IFR [2.7] the estimated average robot density in the total manufacturing industry in the world has a robot density of between 50 and 100. In order to increase this density to about 200, (like current status of the Plastics industry, still way below Automotive), it would take between 1.2 million and 1.5 million new robots to be installed. The Growth Phase model already positioned markets like pharmaceutical & medical in phase 1, the density chart underscores this with hard data and shows the enormous potential for robotics in this sector. If I look at the same date but organized per country for 2009, the leading role of Japan in robotics becomes clear with more than 350 robots per 10,000 workers. Japan has by far the highest density in the world, see also Figure 16. The US only comes at a mere 5th position with close to 150 robots per 10,000 workers. Hungary scores far less, with a density of up to 20-25 robots per 10,000 workers. Europe as collective scores on average 110-120, whish is still below the US and far from Japan.

The density analysis shows that future growth expectation for industrial sectors like food & beverage, pharmaceutical and medical are huge. They are still far away from the current level of automation in the car industry. The BRICs, emerging economic powers Brazil, Russia, India and China, do not yet appear on the 2009 chart. These 4 countries represent a vast economic (and military) power. It is only a matter of time before they too embrace flexible automation using robotics as mean to shift the power balance.

2.2.3 Market Analysis

It may come as no surprise that the automobile industry is in 2010 still the largest user of industrial robots. According to the IFR the number of units sold worldwide almost doubled in 2010 versus the crisis year of 2009, from 60,000 to 118,000 units. It underscores yet again the acceptance of robots as means for flexible automation solutions. Even compared to 2008, which was a record year in itself, a growth rate of 5% was achieved [2.8]. Figure 17 shows the estimated worldwide supply of industrial robots for the last 13 years.


Estimated worldwide annual supply of industrial robots

Source: IFR Statistical Department

Figure 17. Total annual supply of industrial robots worldwide [17]

Four immediate conclusions can be drawn from Figure 17.

1. The total number of industrial robots supplied in absolute value, 118,000 units in 2010, demonstrates the high degree of acceptance of robots as means for flexible automation.
2. The quick recovery from the impacts of the financial crisis 2009 to 2010 demonstrates that robots are linked to capital good investment and industrial output.
3. The crisis in 2009 plunged robot deliveries with -47% to a level equivalent of 1994. A significant drops, but nonetheless not cyclical nor trend related.

4. The annual compounded growth rate since 2002 till 2010 amounts to 7%. A strong grow rate, which will continue for the future.

As I already showed, the position of industrial robots in the product Life Cycle of Figure 12 is that of a Maturity Stage. New strong growth rates are to be expected from spin off technologies and technological developments on the base design. The maturity of the industry will become clearer when analysing the various industries (see Figure 18.)

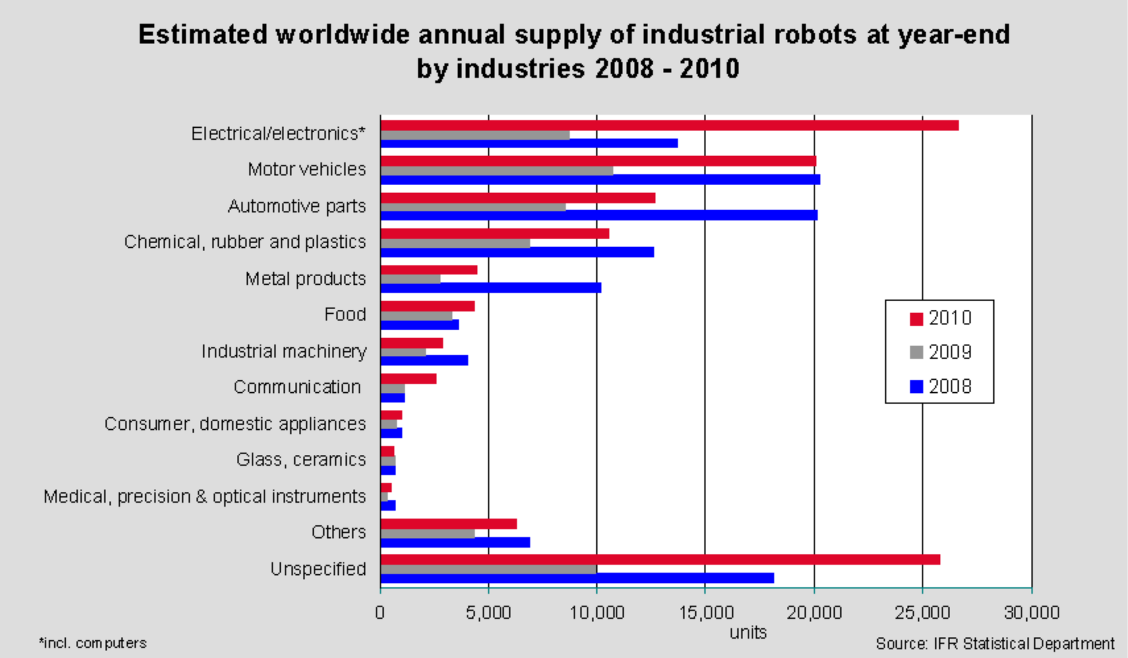


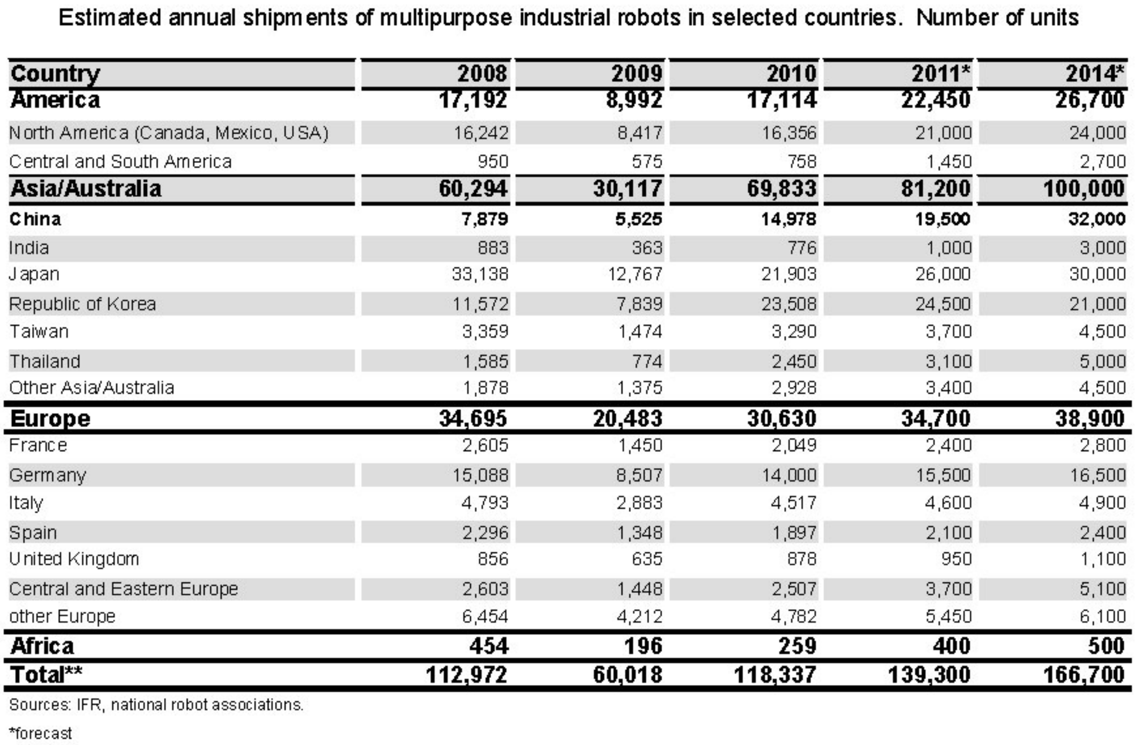
Figure 18. Worldwide supply of industrial robots by industry [18]

If I add the two sectors that make up the Automobile sector, being Motor Vehicles and Automotive Parts, it becomes apparent that this is still the largest user of industrial robots. In total some 32,700 units were used worldwide, close to 28% of the total. The Electronics sector, which includes TV, computers etc., is a good second driver of robots with approximately 31,000 units or 26% delivered. Interesting to establish is the fact that the Metal sector did not recover from the 2009 crisis, as did most other sectors. Robots in the Metal sector are used for arc welding and some handling, often related to the construction markets. The real estate sector is indeed still in a slump following the financial crisis of 2009 and the subsequent sovereign debt crisis in Europe and the US.

Another noteworthy fact is that of the Food Industry. In 2010 they were good for 4,350 units, a 4% share. Small compared to Automobile and Electronics, but its significance is growing fast. 58% of worldwide robot sales to this industry are done in Europe. It is estimated that since the introduction of industrial robots (1960 onwards) the total number of units installed is approximately 2.1 million units. According to an UNECE/IFR study [2.9], the average economical life of an industrial robot can be estimated at 15 years. This implies that the worldwide operational stock of industrial robots is approximately 1.3 million units! The economic value in 2010 can be estimated at US$5.7 billion. The average value per unit for end customers is hence 48,000 US$. The value of a robotics system is much higher. A robotized work cell contains other costly hardware components like customized grippers, cell safety, interfacing of the robot with its peripherals etc. and various software components. In designing robot cells the main problem is that often parts can change form and shape when handled with a passive gripper. A simple solution is using ingressive (needle) gripper for handling these kinds of materials was introduced by Zentay et al in [2.10], and a method for designing such grasping method was given in [2.11], [2.12.]. So to estimate a value, I cannot only consider the naked robot but must add these customized items like grippers and software. An industry rule of thumb to estimate the value of a robot system is; system price is 3x the naked robot price. So the total market for robotics systems in 2010 is estimated at 3 times 5.7 billion, or 17.5 billion US$. I conclude that it is a large sector, which has its own momentum, and will continue to grow.

2.2.4 Geographical Analysis

With the value of the market established and the main industries identified, the next step is to analyse the various markets per economic region. As industrial robots are means of flexible automation, the geographical areas are split in three main areas: Asia (incl. Australia), Europe and America. Figure 19 shows the breakdown of annual sales to these regions.



Estimated annual shipments of multipurpose industrial robots in selected countries. Number of units

Country	2008	2009	2010	2011*	2014*
America	**17,192**	**8,992**	**17,114**	**22,450**	**26,700**
North America (Canada, Mexico, USA)	16,242	8,417	16,356	21,000	24,000
Central and South America	950	575	758	1,450	2,700
Asia/Australia	**60,294**	**30,117**	**69,833**	**81,200**	**100,000**
China	**7,879**	**5,525**	**14,978**	**19,500**	**32,000**
India	883	363	776	1,000	3,000
Japan	33,138	12,767	21,903	26,000	30,000
Republic of Korea	11,572	7,839	23,508	24,500	21,000
Taiwan	3,359	1,474	3,290	3,700	4,500
Thailand	1,585	774	2,450	3,100	5,000
Other Asia/Australia	1,878	1,375	2,928	3,400	4,500
Europe	**34,695**	**20,483**	**30,630**	**34,700**	**38,900**
France	2,605	1,450	2,049	2,400	2,800
Germany	15,088	8,507	14,000	15,500	16,500
Italy	4,793	2,883	4,517	4,600	4,900
Spain	2,296	1,348	1,897	2,100	2,400
United Kingdom	856	635	878	950	1,100
Central and Eastern Europe	2,603	1,448	2,507	3,700	5,100
other Europe	6,454	4,212	4,782	5,450	6,100
Africa	**454**	**196**	**259**	**400**	**500**
Total**	**112,972**	**60,018**	**118,337**	**139,300**	**166,700**

Sources: IFR, national robot associations.

*forecast

Figure 19. Annual industrial robot sales per region [19]

From Figure 19 the following main conclusions can be drawn:

- Asia dominates with a 60% share, headed by South Korea and Japan;
- China doubled its unit volume from 2008 to 2010, and has a total share of ~13%;
- Japan, as only Asian nation, did not recover from the 2009 crisis, realising in 2010 a unit volume well below 2008 levels, losing some of its previous competitiveness to emerging countries like China and Korea;
- While the Americas (read USA) recovered fully from the 2009 crisis, Europe did not, lagging behind. The 2010 absolute value in Europe (30,630 units) is still substantial higher than in the US (16,356 units);
- Germany, the economic motor of Europe is by far the largest user of robots, almost 50% of all European robots are destined for Germany. A part will be re-exported but this is not taken into account;
- The UK has lost its traditional manufacturing power, and is transformed into a service and banking industry. With less than 1,000 robots sold per year, its manufacturing weaknesses are surfacing. In a study it showed that UK companies, despite being

> innovators in product and process technology are falling significantly behind their European competitors in adopting automation. [2.13]

In 2010 China has enjoyed a 171% growth over 2009 and has become the fourth largest worldwide robot market. This growth is due to two factors. First, China needs to increase its production capacities. China is steering more away from the traditional manual labour to flexible automation. And second, the need to produce at higher quality levels. Flexible automation using robots yields higher production consistency and quality, and hence reduces costs for rework and scrap. The forecasts made by IFR for the year 2014 show that the annual shipment for China will surpass the sales volume of Japan, reaching to a level of 32,000 units (Japan 30,000). It is a shocking prediction that China will displace Japan from its undisputed leader position. The installed base of industrial robots will keep Japan in the driver seat for quite some years, but the threat is clear.

In order to compare the regions and the use of robots as mean of flexible automation and thus manufacturing power, it is better to analyse the so called ‘robot density’ than just comparing absolute figures of robot sales and robot stock. The official definition of robot density is the number of multipurpose industrial robots per 10,000 persons employed in the manufacturing industry. A variant exist with reference to density but only related to employees of the Automotive Industry. [2.14] The world’s average robot density in 2010 is at 51 robots per 10,000 employees. This changes dramatically when looking at the various countries. Figure 20 shows the robot density for 2010. Here I can derive various distinctive groups. The first is the top 3; Japan, Korea and Germany with densities of 306, 287, and 253 respectively. I consider these three countries as the most automated in the world.

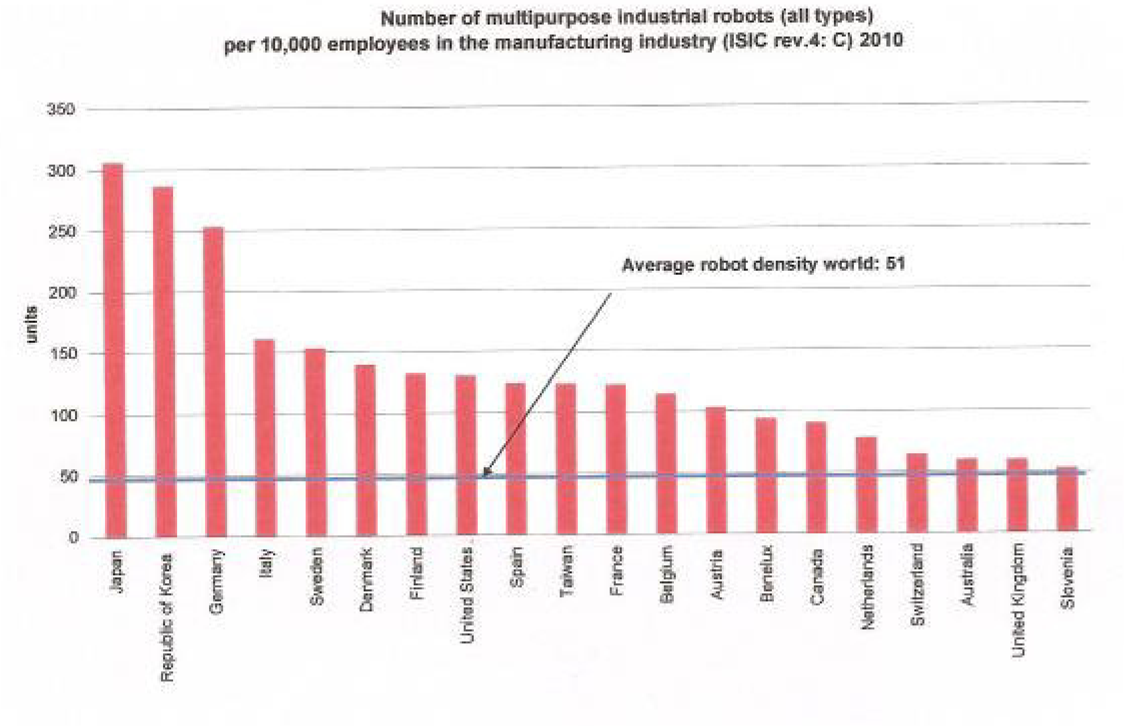


Figure 20. Robot density per country [20]

A second group with still a high rate of robot density, which includes the US (with a robot density of 130), underlines the gap between the top and followers. The US, Italy, Sweden, Denmark, Finland, USA, Spain, France and Taiwan all have similar densities and are considered strong industrialized nations. But the gap is large and in the case of Korea and Japan even widening. Densities in the second group have risen in 2010, but not so much thanks to the high increase of robot stock but more debits to the rising unemployment rates. It might come as a surprise that none of the BRIC countries are represented in the chart. They have a density of 20 or lower. But it reveals the high potential of these regions for flexible automation. The economies of the BRIC countries grow faster than that of the traditional industrialized countries. Both India and Russia have a robot density of 1 in 2010, while Brazil does not score much better with a mere 6 robots per 10,000 workers. Looking at the trends I see a decline in Japan's strength, its density dropping from 2006 (338) to 2010 (306) while Korea increased from 193 to 287.

In the same period China grew from 5 to 15 robots per 10,000 workers. Still a midget compared to the other countries when it comes to the density parameter, but with its vast expansion and economic power I predict this number to grow sharply over the coming years. An example can be found by the announcement in 2012 of the Taiwanese manufacturer Foxconn that it will need 1 million robots over the next three years to replace manual labour [2.15]. Even though these numbers are not realistic, it does underline the enormous potential for the region. It should be noted that China does not produce its own industrial robots, although some foreign manufacturers like the Japanese group Yaskawa and the Swiss/Swedish conglomerate ABB do produce locally in China, mainly to profit from the low labour rates [2.16] and have a local face. Local industrial groups like SIASUN and Boshi, with support from the Chinese government are growing fast, according to a study of Wang [2.17]. It is only a matter of time they will jump from the prototyping phase to the industrialisation of their own industrial robots and UAV's. A Chinese UAV prototype already made successful flights for south polar research in 2007.

2.2.5 The Automotive Link

Using the 2008 manufacturing results for worldwide automobile [2.18] and crossing this with data captured by Figure 19, produces an interesting table as given in Figure 21.

Country	Cars	Commercial	Total		Robots Sold		Robot Stock	
America	9,134,500	7,622,288	16,756,788	24%	17,192	15%	173,977	17%
Asia/Australia	23,703,965	6,367,579	30,071,544	42%	60,294	54%	514,914	50%
Europe	18,796,213	3,380,758	22,176,971	31%	34,695	31%	343,779	33%
Africa	1,334,479	394,698	1,729,177	2%	454	0%	1777	0%
Total	53,329,917	17,932,381	71,262,298	100%	112,635	100%	1,034,447	100%

Figure 21. 2008 Automobile production and robot installations [21]

Although Figure 21 takes all robots installed in a region into account, the relative values would remain equal. The table shows the dominance of the Asian (Japanese) car manufactures with 23 million plus cars produced over the US. For years the US, with 'Detroit' was the center of automotive manufacturing, and was leading over its worldwide competitors. As Kemp et al argue in [2.19], most US car manufacturers have chosen the 'Cost Leadership' production strategy. Although they did invest in robots and flexible automation to achieve cost-down, they failed to follow the market trends of smaller and fuel economic models. Asia (with Japan and China as production leaders) has an output more than double that of the US. It may come as no surprise that the robot stock in this region is triple to that of the US. Asia now produces 42% of all vehicles and possesses more than 54% of all robots worldwide. Where Europeans hit average on both sides, the US is underperforming. The robot stock in Europe is almost double that of the US.

The competitive advantage of the Japanese car manufacturers both in quality and pricing over their US counterparts was already well known. The situation becomes even more clear when the robot density per 10,000 employees in the automotive industry is analyzed. Here Japan, the most automated country in the world, scores with 1.436 robots per 10,000 auto-workers the highest (other industry 191), compared to the number two Germany with 1.130 (other industry density 134). While the electronics sector is highly automated in Japan, in Germany robots are more widespread in their industry. The US follows Germany with 1.12 industrial robots per 10,000 employees (only 69 in other industries). The gap with Japan is clear. As seen before the UK lags behind, with ‘only’ 600 robots per 10,000 auto-workers, an unsustainable position for the mid-term. Already most original UK brands like Jaguar and Mini have been taken over. The BRIC’s automotive density score low is as well, (Brazil 56, India 29, China 105) but are growing steadily. With their growing population and economies the market for industrial robots is enormous. The density number also outlines the fact that growth in non-automotive sectors like Food & beverage, Medical and Plastics is emerging.

2.2.6 UAV & Military Robots

When reviewing the defense related robotics, there is one sector worth mentioning. The Unmanned Aerial Vehicles sector takes up 45% of all robots in defense applications in 2010. The value of defense robots is estimated at US$ 700 million, still far lower than the market penetration of industrial robots. The forecast for 2020 is that this industry will grow to a staggering 20 billion US$. Research conducted by Frost & Sullivan [2.20] for the European Union has indicated that between 2004 and 2008, the number of UAVs deployed globally on operations has increased from around 1,000 to 5,000 systems. Countries with the highest production rates are the US, Israel, France, Germany and the UK. According to Pan [2.21] UAV’s have reached a level of maturity that put these robots on the forefront of international aerospace manufacturing. Although the early UAV’s were mere drones, radio remote controlled vehicles by human operators, the latest generations UAV include built in guidance and control systems and advanced vision and weaponry systems. Although mainly military, in Japan there is a development of UAV use for civil applications [2.22].

2.3 Aging Problems in Society

Most western societies face a growing share of age group 60+ of its population. This group will in fact be the one of the largest demographic groups, reducing the available work force. For this thesis I focus on the effects of the aging of the population in developed western countries as well as upcoming powers like China. Now in 2011 society is on the brink of moving into service robots. A graying population means more needs to take care of elderly and disabled, while at the same time puts tensions on the scarcer labor market. In both instances robotics can be and will be part of the solution.

While there is a relation between increased industrial output and increased robot density, unemployment has some roots in robotics. On the other hand robotics, industrial and service robots, also creates (high skilled) jobs. Doom scenarios prevail among neoclassic economists that foresee a collapse of employment, purchasing power and in fact economies if full automation combined with artificial intelligence becomes reality. There is certainly a degree of replacement of human labor skill level brought by robotics. This is true for industry where qualified workers are being replaced by ‘common’ robot operators but as well in the military field, especially where UAV’s are concerned.

2.3.1 Aging Population and Robotics

It is no news that the world’s population is aging, at an alarming rate even. Longevity is increasing due to improved health care and care itself is available for more and more people. Also in the developed world fertility rates are dropping. Its effects are manifold. The demographic changes will bring challenges, and some meaningful questions arise in relation with robotics. Is there a relationship between the growth of industrial automation, deployment of UAV’s and the emerging market for service robots with respect to the aging population? Can robotics be {part of} the solution for the problems caused by an aging population? First, let’s look at the facts surrounding this phenomenon. According to HelpAge [2.23];

- Almost **1 in 10** people are **over 60** years old;
- By 2050 **1 in 5** people in developing countries will be **over 60;**
- Even more scarier: people aged over 60 **will outnumber children** aged 0-14 by 2050.

Besides all the demographical, environmental and social issues that a growing aged population brings, I concentrate on the relationship between aging population and the need for robotics. If I review the relationship between age and workforce availability.

I see a common picture as displayed in Figure 22.

			Age group			
	25 -	54	55 -	64	65+	
Region	Men	Women	Men	Women	Men	Women
World	95	67	74	40	30	12
Developed Regions	92	78	65	46	15	8
less developed regions	96	64	77	38	37	14
Europe	91	80	58	39	9	5
Asia	96	64	76	37	34	11
North America	91	76	70	59	21	13

Figure 22. Labor force participation rates, 2008, by region, gender and age group [22]

I conclude from this table that labour force participation declines faster in developing regions than in other rural and/or less developed areas. Europe in particular has a low participation rate at higher age levels. It is these factors combined that are alarming, with the population aging more and more, it means that less human labour is available for reaching the required levels of industrial output in Europe and in the developing countries in general.

Then there is also the need to take care and support of the elderly and disabled. For workers with pension coverage, rules governing pension entitlement have a strong effect on timing of withdrawal from the labor force.

Also many European countries operate with a mandatory retirement age, and push out older workers at a certain age. Wise showed in [2.24] that in addition to the push factors, there are also financial incentives to retire at the national official retirement age. Factors like long-term disability and sickness linked to employment benefits played a strong role in facilitating early retirement in some developed countries.

Singling out Asia shows that Japan currently has the largest share of old age people in the world, with 27% of the population aged 60 and over. Following a UN report cited by Bloom [2.25,] it is estimated that this number will rise to 44% by 2050. In fact more than 70 countries, representing about one third of the global population, are expected to have an old-age share exceeding Japan's share of 27% in 2005.

Countries with the Highest 60-and-over population Shares 2005 & 2050

	2005 in %		**2050 in %**
Japan	27	Japan	44
Germany	25	Korea	41
Italy	25	Singapore	40
Sweden	23	Germany	40
Greece	23	Bosnia	39
Bulgaria	23	Italy	39
Latvia	22	Cuba	39
Portugal	22	Portugal	38
Belgium	22	Bulgaria	38
Austria	22	Poland	38

Figure 23. Countries with highest population share [23]

In above Figure 23 I detect a problem arising in the coming decades for countries like Japan, Korea, Germany and Italy. With 60+ population shares of 40% and over, this represents a large group of elderly people who, in general terms, consume more than they will contribute. Apart from creating problems in availability of medical and social resources it means also a strain on the availability of workforce, as birth rates are declining.

Oddly enough these are also G-7 country members, relying heavily on export (machine building). Zooming in on the BRIC zone, and in specific China and India I can conclude the following picture.

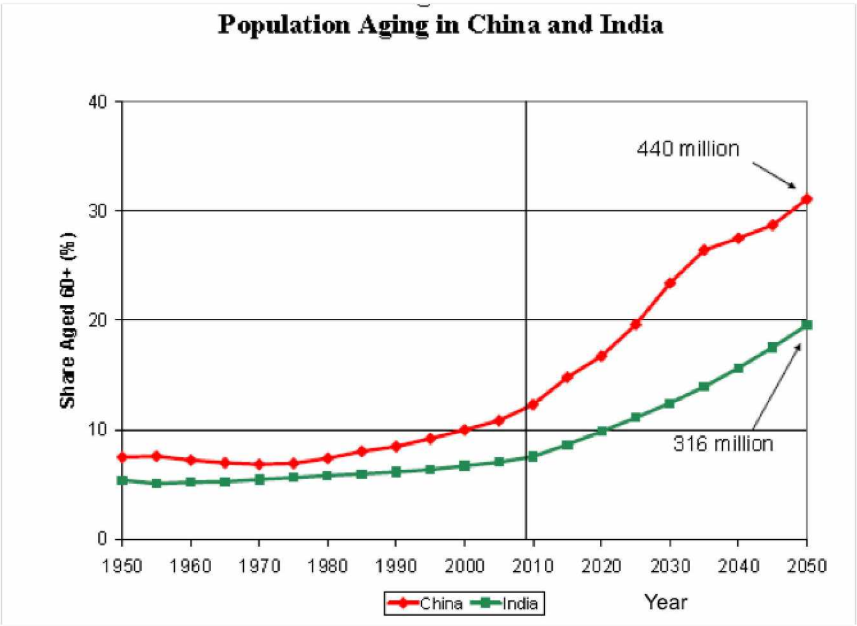


Figure 24. Population aging in China and India [24]

Figure 24 shows that both China and India have in 2010 a modest score in share of over 60+ population. However, it is also clear from the expectation displayed in the graph that China's population will age exponentially the coming decades, rising well above the 30%. China, which has strict birth rates of maximum 1 child per family, might jeopardize its economic prospects. In absolute numbers this is a staggering 440 million Chinese aged over 60 in 2050. With the continuing economic growth rates of China, every industrialized country's industrial platform will be challenged.

As Peterson [2.26] stated already around a decade ago, a situation where there is a lack of available human labor combined with a need to provide socially, economically and medically for a growing group of elderly and disabled is not an economically sustainable situation. Solutions are at hand. A step already underway in some western countries is the raising of the so called ‘exit point’ of active labor. The age at which humans retire is going steadily up from 65 to even 70 years, but this policy is not widely adapted. Another solution is that the work force has to be enlarged. Figure 22 also shows the clear gap between active men and active women. By employing more women the growing gap between needed and available work force can be reduced. To whatever extent this can be realized is questionable. Enlarging the work force can also be achieved by immigration. This option however is discarded as it would require too high numbers to compensate for the aging population and is politically not supported when large volumes are considered. Automation, using industrial and service robots, could be the new pillar.

2.3.2 Aging versus Robot Density

According to Microsoft’s founder Bill Gates, every home will have a (service) robot by 2020 [2.27]. He considers the development of the robotics industry in the same way that the computer business did 30 years ago. By assuming the correlation between the current population shares crossed with current robot density (robot density is the number of robots per 10,000 workers), I create the following grid.

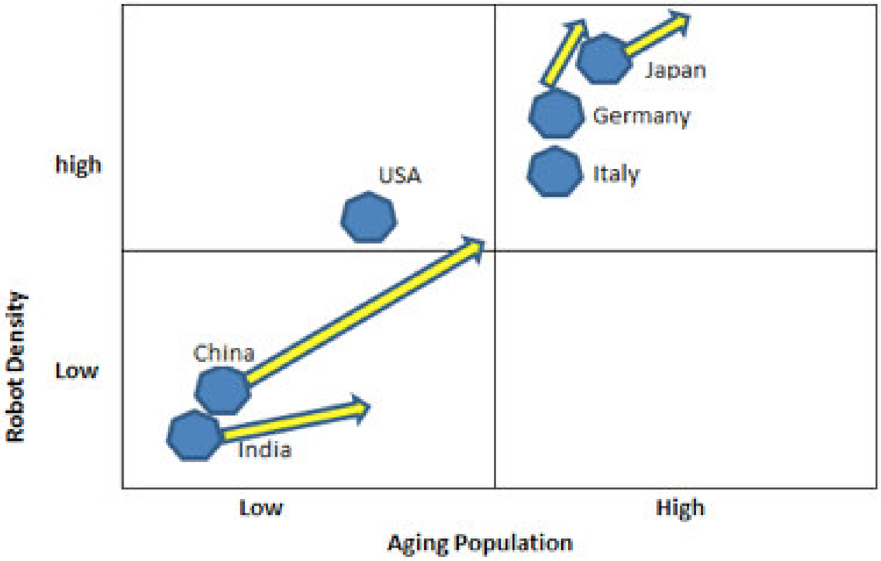


Figure 25. Robot density versus share of aging population [25]

Where in 2010 Japan has the highest share in its population of 60 and over, Japan is also the country with the highest robot density in the world [2.28]. Japan uses robots at an unpaired level;

it has a robot density of close to 320. From Figure 25 I can conclude that not all developed countries are in the same situation. Japan, with its aging population needs to continuously invest in Research & Development on both industrial robots as Service Robots sides.

The growth potential of China, and to a lesser extend India is clear. While these countries too will undergo changes in population, they can benefit from the experiences and advances made in other countries to grow their robot densities faster and steeper. The BRIC countries can benefit most from investments in automation as their economies expand while their population ages. Shelton in 2005 [2.29] pointed out that the R&D investments or gross expenditures on research and development made by China already are with 18.9% double digit and has been doubling real R&D investment about every six years. Compared with a mere 1.7% for the US and 2.2% for the EU. In absolute values China spends approximately 1/3 of the European amount, and 1/4 compared to the USA. I estimate it is only a matter of time before China catches up and takes the role as world's leading country.

Oddly enough, China has even in 2012 no own industrial robot brand. It might not be a surprise that Taiwan based company Foxconn (Hon Hai Precision Industry Co.) announced plans to begin building industrial robots. They plan an initial number of one million industrial robots for its own factories. This represents roughly the sum of all current industrial robots installed. Foxconn now employs more than 300,000 workers.

A million industrial robots made by Foxconn will nearly double the number of industrial robots in the world. It could put China at the top of the automation industry. For western developed countries like Germany and Italy it will be more difficult as living standards are already high and the share of "over 60+" active population is too low in competitive terms towards other nations, as seen in Figure 20. Europe does have a roadmap, R4H (Robots for Healthcare), to investigate the areas and manners to use technology as an answer to the challenges of the aging population. In Europe health care automation will most likely start in surgery by all kinds of robotic systems. Service robots will be a second approach to assist elderly and people with disabilities.

2.3.3 New Applications

In Japan there exist already a very high acceptance level for robots and automation in general. The jump from toys to toy robots to finally service robots is therefore not very large. What might be unacceptable in 2010 in Europe; elderly tended by a service robot, in Japan this is a likely scenario. Nurse robots in Japan and Korea already assist elderly and service robots are being introduced on a small but growing scale [2.30]. These service robots assist elderly and disabled people in order to live more or less independently and provide some entertainment. Improvements are being made on face detection, sound localization among others. Examples are not far off. In fact, during the International Robot Show in Tokyo held in November 2011, operational and prototypes of service robots were shown. An example of the use of service robots in daily life is illustrated in Figure 26. Here a humanoid robot is used -instead of humans – as practice patients for dentists in training. The displayed robot is a 10-axis robot - named Showa Hanako 2. It has a silicon skin and has speech recognition capabilities. It can listen and react to commands given to it by the dentist in training. Also it is able to simulate among others, openings of the mouth and eyes, express fear etc. The tongue itself has two degrees of freedom and the robot can even simulate natural movements and choking. The robot even gets tired of holding its mouth open.

Figure 26. Dentist trainee robot - Showa Hanako 2 [26]

As the example shows, the advantageous are numerous, and the fields of application can be manifold. The aging of the various populations is therefore an area for growth for automation and robotics. In Europe the field of medical purpose robots pushes ahead. According to Rensma [2.31], member of the Dutch innovation agency TNO, this industry could be worth anywhere from €40 billion upwards, as the attraction for authorities trying to plan for increasingly ageing societies is enormous. Lopez [2.32] estimates that the development of service robots will follow a similar path as that of the industrial robots. Wishful thinking or a reality, in any case there is still a gap between the R&D prototyping and commercial rollout of service robots. As I showed in [2.33], robots used for medical purposes are now built in a modular form. These robots have become scalable towards the required application, and can be tuned via parameter settings. Indeed similar as can be found in industrial robots. In addition, adding dedicated instruments to the robot's universal end effector and wrist design and adapting its many internal control sensors achieve versatility for medical robots. Again an experience gained from industrial applications.

US chip manufacturer Intel has set up a division dedicated to home automation and elder care. Its HERB project (Home Exploring Robotic Butler) aims at overcoming the existing gap between current service robotics and application of robotics in ordinary homes through mapping, searching and navigating through indoor environments. Here also industrial robotics elements and experiences are applied to develop commercial and practical service robots. In summary I conclude that the industrialized developed countries are using their lead in industrial robots to enter the field of health care and service robots. The market needs translated through the decline of the workforce and aging of the population is clear. Flexible Automation will play a key role in the coming decades to transform robots from sophisticated machines into tools to be used in daily life, like a car, PC or smartphone.

2.4 Changes in Human Society lead by Robotics

Just as important is the functionality of a robot, is the way it is perceived by its users. Robots impact humans in various ways. I review here the fear and fascination for robots and the impact that robotics has on the labor market. The way humans interact with robots can limit their use, or stimulate it.

2.4.1 Fear and Fascination for Robots

In society robots, in whatever form they might come, surround humans. Our children, our dearest ‘possessions’, play with toy robots. Our homes have robots that autonomously cut the lawn, vacuum the house and clean the pool. The factories that produce our bread, water and cars all operate from a low to a very high extent on industrial robots. In the latest wars, like the war on terror in Afghanistan, surveillance by UAVs make the difference between life and death for the soldiers in the field. Our hospitals are equipped with robots. Robots are used in medicine to comfort and tend patients. And let’s not forget the large influence and certainly the typesetting around robots created by Hollywood for entertainment purposes: Star Trek series (1966), The Star Wars movies (1977), the cult film Blade Runner (1982), Schwarzenegger’s Terminator (1984), I, Robot (2004), the animation movie Wall-E (2008) and many more. Most of these movies work around the theme of man against machine, artificial intelligence taking over control, and/or personalisation in robots. Although these movies reflect the time of society when they were made, the common thread is a high form of artificial intelligence and the struggle of humanity to keep in control. A clear example can be found in the worldwide attention for the matches of Deep Blue’s chess computer in the ‘90s against world champion Gary Kasparov. It underscores the fact that mankind is fascinated by machines. In his book “*Sublime Dreams of Living Machines”* Kang explores this fascination throughout the centuries [2.34]. He argues that the delight, amusement, and amazement that people experience in the face of the self-moving, life-imitating machine are mixed with a sense of unease that can be magnified into full-blown horror under certain circumstances. As people were amazed by the Babylonian water clocks of 1400BC, the same applies to the mythological Trojan horse (a machine like replica of a living creature), which implanted so much fascination that the Trojans opened the city gates for it and became ambushed by the Greek [2.35].

The fascination for machines in general and robots in specific lies in the ability of the machine to perform tasks – often better – that before were only executed by humans. At the flip side of the coin, at the other end of the scale of fascination, is fear. The human inbred fear for the unknown, the fear that is generated when not being ‘in control’. General ignorance only makes the ability of the robot only more magical. It is very humans to organize reality into a clear and simple worldview, using series of opposing binaries, black versus white, man versus woman, yin versus yang, day versus night, dead versus alive etc. Disruption to these simple and clear patterns disturb and disrupt. Gay people are still having large difficulties of acceptance, moon eclipses drove people with fear. Robots are machines, non-living, yet exhibit all features of being alive. In 2012 androids can mimic most human body language. An informal, non-random survey run by the ThinkArtificial.org blog showed that 16.7% of the respondents find the idea of intelligent machines frightening [2.36]. And this was among young American tech oriented students. The number would rise for the general public in all age groups. It demonstrates that the have difficulties in dealing with robots, to see it as a mere machine, as opposed to i.e. a coffee machine. Introduction of industrial robots in western factories occurs through phases, where in the first phase a robot substitutes a worker to execute simple tasks typically takes up to two years [2.37]. It takes up to two years to overcome the fear of robotics, to understand and accept the technology and adept it to management's needs.

2.4.2 Uncanny Valley

Fear for robots is omnipresent if I consider the studies of robotics professor Masahiro Mori (1970) related to the **uncanny valley** [2.38]**.** The uncanny valley stipulates the human response to the degree of "likeness" of robots to humans. The hypothesis holds that when robots like androids (see Figure 27.) have a near complete "look & feel" like real humans, it creates a response of disgust and repulsion. In Figure 27. the so called valley is the dip in the graph when robots almost reach human likeness. Industrial robots start of the graph and indeed do not provoke a large emotional response. Toy robots and stuffed animal do create a more positive feeling.

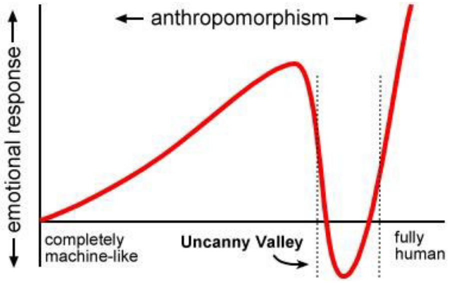


Figure 27. The Uncanny Valley [27]

An artificial arm/or leg is not pleasant for humans like to look at. On the same level one finds that a dead body of a human could also be positioned in this point of the graph, having all the elements of being human but lacking the “life”, same as for robots which resemble humans to a high degree of perfection. The uncanny valley effect stresses the need in design of robots, especially androids. For a successful introduction of these types of robots in the service industry for instance, the design and texture of the robot has to be taken into account, taking it out of the valley and into acceptance.

Writer George Orwell in his 1949 novel ‘*1984*’ [2.39] used already in that period technology as demonstrative power to control humans. He predicted a future society controlled by technology, surveying its members through Big brother. It instilled fear as the controlling component. Now, some 70 years later reality is not far off, the spread of CCTV (Closed Circuit Television) cameras worldwide is staggering, Big Brother is watching indeed.

The issue at hand has to be positioned in the right context however. These cameras and surveillance systems bring peace and order in our lives, but do not instil fear. Robots are stupid machines, it are the humans that operate them and program them that can be dangerous. In conclusion I can state that fear for robots and artificial intelligence is real and should not be underestimated. But perhaps more than fear itself is the possible danger of what humans can do with technology. Nuclear power brought both prosperity and destruction. If we fear robots, machines that we created to mirror ourselves, it is that we fear ourselves.

2.4.3 Laws of Robotics

So overtime society has embraced technology, pursued automata’s and robots, in fact trying to create a human machine. With the anxiety and fear as described in the previous chapter it becomes clear that ethical issues started to play. Guidelines are necessary to govern these human look alike. It was Isaac Asimov, a 20th century science fiction novelist and scholar who was looking for ways to counter this fear, the uneasiness as it were that is produced or attributed to robots. Asimov created in 1942 the Three Laws of Robotics [2.40]. They were introduced by him in his 1942 short story "Runaround", but have been part of previous work around robots. The Asimov laws of robotics are:

1. ***A robot may not injure a human being or, through inaction, allow a human being to come to harm;***
2. ***A robot must obey the orders given it by human beings, except where such orders would conflict with the First Law;***
3. ***A robot must protect its own existence as long as such protection does not conflict with the First or Second Laws.***

Why did Asimov, writer of I, Robot and who gave input to the Star Trek series, came up with these laws and why in this conjecture? Isaac Asimov was truly convinced that robots should have underlying rules to control their behavior. They were for sure a good attempt given the worldview in the ‘40s but such high-level rules are simply impracticable when you look at it from a software engineering point of view. The three laws together lack consistency. Asimov used the three laws in many of his robot stories, as the main focal point. His robot characters would run into unsolvable dilemmas regarding the laws, as there is no boundary for a robot between for instance a good and a greater good. The ethical dilemmas are clear and still valid at present time.

If I scrutinize these laws with current knowledge I conclude that the first law is aimed at limiting the autonomy of a robot, protecting humans from their actions or inactions. The rule accepts implicitly the existence of robots, but robot freedom should be limited by the application of Law #1. It serves as a kind of philosophical automatic circuit breaker. Still, Asimov’s first law is omnipresent applied for industrial robots. In fact, in Europe CE regulation stipulates all safety norms related to robots and their interaction with operators. [2.41]. Large focus is made on protecting people from getting harmed by robots. Industrial robots are standard equipped with double safety circuits, governed often by separate microprocessors.

The robots operate in work cells; guarded by hardwire fencing, pressure mats and light screens, all for safety purposes. If an industrial robot could hurt or kills a person (which sadly does occur), then the question that arises is who is at fault? In many cases the fault will lie at the designer of the application (software) or operator of the robot. However, the more robots work autonomous, the less clear the responsibility becomes. It is the extent to which humans allow a robot to decide to take action instead of a human. The second law – a robot must obey orders - inclines to limit the autonomy of the artificial intelligence of robots. If robots are considered to work autonomous, following and deciding according to their own logic and rule set, humans don't want them to turn against themselves and do harm.

If the first law of Asimov was the before mentioned circuit breaker, than law 2 can be characterized as an "emergency brake". Humans must stay in control no matter what. Despite the Hollywood pictures, and despite the advanced stage of technology, it is not a real danger that humanoid robots will become highly intelligent and take over control. There is no evidence to support this. For sure man will more and more interact with machines, as can be seen in daily live by the use of smart phones and PDA's (Personal Digital Assistant). Still a machine is a machine, it needs power and can be turned off.

The third law of Asimov intends to transfer identity and 'self' to a machine. Science fiction aside, most if not all robots operate from a rigid instruction set and are just not capable have a sense of judgment and to base decisions on feelings and emotions. Machines have no self, no matter how capable. If they portray emotion, it is a copy of a programmed or learned instruction set. It is just impossible to foresee all possible worldly outcomes within the endless contexts and than to program these outcomes into robot intelligence. Flying a plane without pilots is technically possible and economically attractive; yet, even in 2011 all commercial airlines employ two pilots. Why? Because unpredictability just cannot fully captured by artificial intelligence.

Murphy and Woods [2.42] proposed a more realistic "The Three Laws of Responsible Robotics":

1. A human may not deploy a robot without the human-robot work system meeting the highest legal and professional standards of safety and ethics;
2. A robot must respond to humans as appropriate for their roles;
3. A robot must be endowed with sufficient situated autonomy to protect its own existence as long as such protection provides smooth transfer of control which does not conflict with the First and Second Laws.

Futurist Ray Kurzweil (2005) approached the concept of **Technological singularity,** a hypothetical future emergence of an artificial intelligence larger than those of human [2.43]. It results in an end of separation between what is human and what is machine, the ultimate singularity. It is a fact that powers of computers and other technologies are increasing exponentially. I argue that it might eventually be possible to build a super computer that is more intelligent than man. This machine itself could design and invent a yet more capable machine, setting of a technological singularity.

I conclude that as technology evolves the ethical questions on responsibility become more stringent. Protecting humans and not losing control are elements as old as Asimov's laws and still apply in 2012. No three laws will ever meet the requirements and dilemmas with regards to robots, their degrees of autonomy and our responses to them. Service robots already tend elderly in Japan and this is accepted by the Japanese society. It is the ethical question to what extents do robots interact with humans and to what extent can robots be autonomous? It is not the (ultimate) intelligence in a robot that matters; it is how it affects us humans emotionally that will be the determining factor.

2.4.4 Robotics versus Labor

Robots found their way in our factories since the 1970s. Industrial robots have sustained a steady growth and are now entering a maturity phase in the product life cycle. Military robots and service robots are just enjoying their start-up, entering a large growth phase. In Japan the ratio of robots versus 10,000 factory workers is well over 200! The robotics industry is a multi-billion global industry, touching every industry for its applications. More than one million industrial robots are working around the globe in 2012. That implies at least 1 million if not more humans deprived of labor and income. In Japan, birthplace and front-runner in robotics, already androids with human like look and feel start to work in roles in retail commerce and reception work. These androids will achieve sooner or later a basic level of self-awareness to able to interact 'naturally' with humans. In general there is a trend that more and more simple human tasks are being taken over by machines, from the bank teller to the check-in counter at airports, see example of Figure 28.

Figure 28. 8-axis android receptionist with integrated vision from Kokoro Inc. Japan [28]

Until the year 2000 industrial and service robots have competed with humans only for basic, labor intensive, hazardous and/or repetitive jobs. In most cases, jobs unfit or unwanted for humans. Robots that took over jobs in factories started with the basic repetitive work are now step-by-step moving into the more intelligent and sophisticated tasks.

Robots, thanks to the advances of microprocessors, neural networks, sensor technology and devices using cloud computing, can now look and feel. In 2012 industrial robot can assemble parts using vision and force sensing, and operate autonomous. How soon robots will robots be able to perform nearly any normal job that a human factory worker performs today?

AGV's or Automated Guided Vehicles already operate in highly robotized factories to transport goods and material to and from the robotized cells. Our supermarkets have automated self-serve checkout lines. Our cars can park backwards automatically thanks to vision system and sensor technology. Where does that leave us? And more important; where does it all lead to? In the end, in our capitalistic society, all of these robots will eliminate a large portion of the jobs currently held by human beings. Basic, simple jobs are being taken over by robots.

This outlook is based on capitalism where cost cutting is realized by flexible automation in our factories, stores, banks, hotels, airports, factories, construction sites etc. It is already taking form and will undoubtedly leave huge numbers of people unemployed, as illustrated in Figure 29. In 2012 even many video rental stores do not employ humans anymore. In the fast food industry robots can be employed to cook hamburgers and fries and deliver it to the counter. Robots already are being used to prepare sushi, act as bar man, as tennis instructor and so on. On the other hand, this momentum creates jobs as well. It creates labor for well-educated engineers, programmers and scientists, and a new branch in education among others. The impact on our society the coming 25 years will be enormous, and is not taken seriously by the various social stakeholders until it is too late ... too late to go backwards.

Figure 29. Economic impact versus social impact of robotics [29]

In fact, humans cannot compete in the long run with much lower labor costs introduced by robotic automation. Car manufacturers in a typical low-wage country like India rely already on robotics as the main work force, causing social conflicts [2.44]. In the US the program "save your factory" was started beginning of this decade, promoting the use of industrial robots as a way to keep manufacturing within the US instead of outsourcing production to low wage countries.

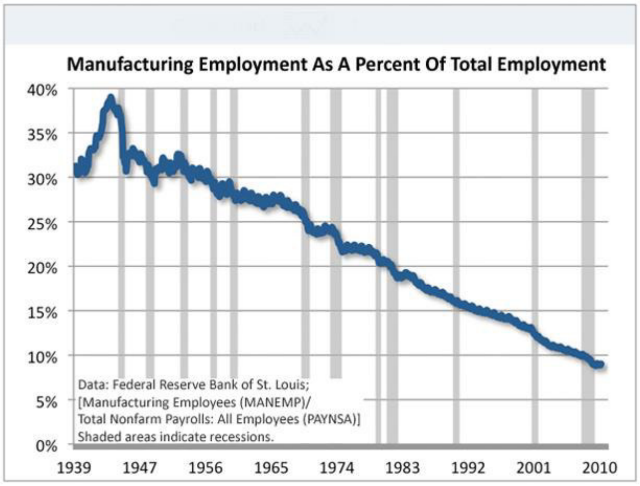
The program appeals to a socio-economical need within humans. But it comes at a high price; the exchange of low cost jobs to robots. This is a clear effect of robots taking over human labor, and hence decreasing welfare for the involved workers, for an economic and social benefit. The return on investment ROI of a typical robot installation is currently a year or less. So it is inevitable that robotics and flexible automation will replace human labor. Western societies should therefore focus more on advanced job training, R&D, innovative creativity and knowledge management.

An investment is needed to 'educate the masses' in order to provide an economic sustainable model. Unemployment will gradually rise over the coming years due to the ever-growing capacity of robots. Welfare and employment go hand in hand.

2.4.4.1 Is Robotics Creating or Destroying Labor?

With the prices of (industrial) robots falling, the cost of labor rising, and the technology continuously improving, the demand for robotics keeps growing. According to Sakakibara [2.45] robot sales in 2011 will rise approximately 18% to about 140,000 units. This means a new peak level, while a continued increase will happen in the period between 2012 and 2014 of about 6% per year. Sales will reach levels of about 167,000 units in 2014. This means that the operational stock of industrial robots operating in the factories worldwide will increase to about 1.3 million units at the end of 2014.

One can argue that these robots have taken the place of manual labour. To a certain extent this is true. Robots are indeed used to replace human labour, i.e. robotised arc welding versus manual welders, pick & place robots versus human pick and packing lines, robotised load/unload of machines versus factory workshop labour, automated paint booths versus manual painters, automated meat cutting versus butchers. The list is endless. Labour volume in manufacturing indeed decreased over the last decade. I conclude that while a sharp increase in automation and robotics occurred also the industrial output increased. So the reduction in labour has been offset by higher productivity and output, which benefits and stimulates economies and thus labour participation. A larger and a higher degree of flexible automation in our factories create a higher output, and so shifts labour from factory floor to services oriented labour.



Data: Federal Reserve Bank of St. Louis;
[Manufacturing Employees (MANEMP)/
Total Nonfarm Payrolls: All Employees (PAYNSA)]
Shaded areas indicate recessions.

Figure 30. Manufacturing share of employment in US [30]

Figure 30 shows the increased downward trend of manufacturing share as a percentage of the total employment in the US since 1939 till 2010. It shows that even in periods outside recessions the share is falling. Since 2000, when the US ‘only’ had a robot density of 52, the manufacturing share dropped from 13% to less than 9% in 2011. Its robot density went upward from 52 to 110. Output rose 9% over the same period. Unemployment increased, but only sharply during the last crisis, starting 2009, see Figure 31.

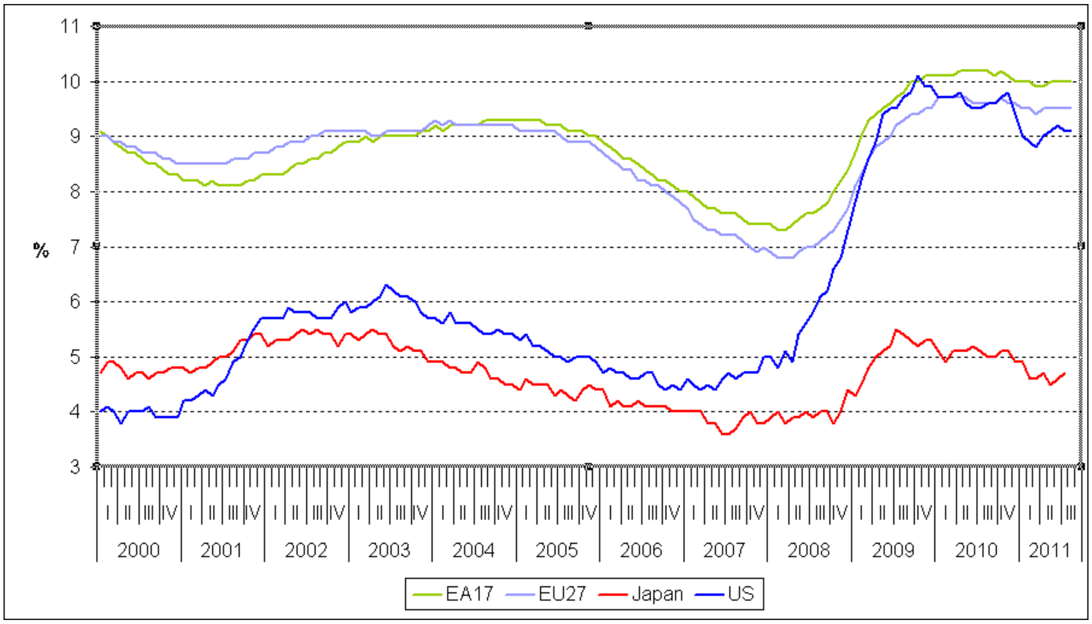


Figure 31. Unemployment as share of total per region [31]

Following this analysis I concluded that the use of industrial robots does have an effect on the share of employment in manufacturing, but not on the total. According to Liveris [2.46] nations must focus on investments in automation for manufacturing to stay competitive. Germany is hailed as a positive example, a high-wage country that has revived its advanced-manufacturing sector. It was able to convert its trade deficit of $5.9 billion in 1998 to a trade surplus of $267.1 billion in 2008.

The German government invested in advanced manufacturing, and those investments are paying off. According to a study by Gorle [2.47] the approximately one million plus industrial robots currently in operation have been directly responsible for the creation of close to three million jobs. These jobs come from the newly created robotics industry itself. It includes the various robotics manufacturers and their sub-suppliers for i.e. reducers, castings and gear boxes. In addition there is a large group of large and SME (small medium enterprise) as line builders and/or system houses, responsible for the integration of the robots into work cells.

Next is the group of end users, as robots need to be operated and maintained. Also, the growth in robot use over the next five years will result in the creation of one million high quality jobs around the world. So according to this study, robots will help to create jobs in some of the most critical industries of this century: automotive, consumer electronics, food, solar & wind power, and advanced battery manufacturing to name just a few. If I would include the indirect jobs, the employment grows even more. Increased robotics market signifies a positive expanding effect towards indirect growth of labor. Here one can think of the increase in volume for transport companies, business travel, restaurants, shops etc. In total robotics can be attributed to 8 to 10 million jobs.

Critics to this viewpoint do exist. Ford in [2.48] present evidence that a tipping point towards automation is close. If humanity keeps on and automates even more, the economy cannot absorb the newly unemployed due to automation in other sectors and hence it would reduce the purchasing power of the people. Unemployment will rise (and is rising) more and more through the automation of many service jobs, like automated bank/airport tellers, self-checkout cashiers in supermarkets, on-line shopping versus true shopping. The growing group of unemployed people would simply not have enough purchasing power to consume the products brought forward by the economy. This would push for even more price decreases, and more automation. A vicious circle.

It would in fact comply with the so called “Luddite fallacy”, the neoclassical economic belief that labor saving technologies will ultimately lead to mass unemployment and an over-automated society where manufacturers take and. The original Luddites were early 19th century English textile workers who smashed the new textile machines to protect employment [2.49].

Automation in textile in the 19th century did not stop the economy, employment and output from growing. Nor did it happen with the automation of agriculture and that of car manufacturing. On the other hand there were other manufacturing industries to absorb the employment. In a theoretical sense an all automated society would lead to the Luddite fallacy.

According to Tabbarok [2.50] there is no correlation between unemployment and automation. Reversely, productivity growth leads to higher real wages and lower unemployment. Full automation as requirement for the Luddite fallacy, will not and cannot be reached due to various factors. The main ones are:

- Technical limitations, (dynamics, cycle time, processing power limitations);
- Small batch series (flexible automation is not ‘flexible’ enough);
- Poor Cost/Benefit ratio or too low return on robot investments (Automation is possible but is not economically viable);
- Complex Human-Machine interfaces in case of service robots (dealing with a human is not the same as dealing with an industrial process);
- The inate human desire to deal with humans (doctors, artists, teachers, entertainment, and so on).

While technology push might overcome some obstacles in the long run, on a short term basis these are valid barriers to refrain from reaching full scale automation. The benefits of robots, whether in industry or service robots are clear. The use of robots overcomes inhumane working conditions (high payload, environment with emissions, high repetitive strain) and hence stimulates production and quality of life of employees. In addition, new industries keep emerging. Like in the Energy Sector: Bio fuel, Solar Industry, Wind Power, Lithium Battery manufacturing all need human labour, and will need automation to make it affordable. Other examples can be found in aircraft demolition, smart phones and tablet industry, bio farming and Eco tourism, all will require human labour. The rise of robotics and the change of types of human labour go hand in hand.

2.4.4.2 UAV’s versus Human Pilots

When I review the defense related robotics, there is one sector worth mentioning. Unmanned Aerial Vehicles (UAV) have been around only for a mere 15 years. They were introduced in the second Gulf War in war theatre. Their main advantages over man-flight are clear; less risk, more autonomy and more cost effective. While in use since 2001 in the US Army it use has multiplied by a factor 80 till 2010 [2.51].

It function started as reconnaissance but has been extended to search and destroy capabilities. Traditionally these craft were flown by ex-fighter pilots. According to Hoffman [2.52] the US Air Force is training airmen rather than manned aircraft pilots to fly unmanned aerial vehicles. This represents a huge saving, some $1.5 billion over six years. Currently the US Air Force spends more than $2.6 million to train a fighter pilot. Training for an UAV pilot would be a little more than $135,000 per pilot. Typical a case where automation first removes humans from hazardous places and overtakes intelligent skills to be operated by ‘common’ skills. Not far off from the earlier example given where the automotive paint lines before required highly skilled painters only to be replaced by common operators, which run the robotized paint lines.

2.5 Conclusions

From the Product Life Cycle model I conclude that robots for industrial use have followed a normal growth path and are in a maturity phase. This implies that for the next 10 to 20 years the volume used will continue to be large. Robots will continue to change the way products are manufactured and subsequently require full focus from managers, education and R&D platforms in industry worldwide.

Most developed countries show a high degree of robot density, but there is an enormous potential for growth in sectors like pharmaceutical, food & beverage and medical industries. The emerging geographical markets, mainly the BRIC countries, will enjoy even faster growth given their current poor density levels. Both robot density and growth phase stages show that the peak has not been reached. Industrial robots are commodities, as concluded via the PLC analysis, making the barriers to acceptance of military robots and service robots disappear. Military robots in general are lagging behind on their industrial cousins. Most Military Robotics is still in its Development Stage. Exceptions that I can mention are the UAVs. Their usage experienced a high growth and acceptance rate based on their successes the last 10 years in the war on terror. These successes of UAV’s showed military leaders the advantages over human operated devices.

The steady growth of UAV deployment will continue and will lead the way to acceptance of other military robotics. The highly concentrated industrial robot market however, with clear economic objectives, is not concerned with military robots. This is a gap that exists, and will remain. The military sector experiences a shift from skilled human labor to automation, especially in the field of UAV's. The military sector is likely to grow, and it follows the same growth characteristics as those that can be found in industrial robots.

As I mentioned strive for automation and robotics is as old as the first human societies. However the past 15 years have experienced an enormous explosion of artificial intelligence, computing capability and robotics within our society. Driven by the technological advances of microprocessors, neural memory and vision systems the robotics sector is changing the landscape fast. Most developed countries already show a high degree of robot density, but there is an enormous potential for more growth where basic jobs will be taken over by robots.

Our populations are aging at an unprecedented rate, while western societies are embracing technology to increase output and efficiency. Japan is by far the most automated country in the world, but also has the largest share of elderly. R&D Investments in automation can improve a countries competitive position while remaining a high cost country, like Germany. China's star is rising, with large growth numbers in investments, robot density, but is also facing the growing share of elderly. It is to be expected that China will equal Japan in the future when it comes to yearly installed robots. China has no own robot manufacturing but indications show that in the near future this is likely. Service robots will come in force, most likely to roll out commercially first in Asian countries like Japan and Korea. Their growth will follow a similar path as that of industrial robots.

Although it is undeniable that robots create unemployment they also create it. This amount is estimated at a total of 8 million jobs. So far the created unemployment has been (partly) absorbed by other manufacturing sectors and the growing service sector. A theoretical total automation of manufacturing would lead to huge unemployment, loss of purchasing power and thus dramatic social changes. Upcoming industries with new needs, technical and practical issues however will make this unlikely. Although fear for robots exists, society should fear more the social and economic impacts that this expanding growth of robotics will bring. Unemployment can rise to enormous heights, and lead to an unsustainable social model where large part of human society cannot participate in the capitalistic model anymore, as there will be a surplus of human labor. The welfare of the people comes under attack if no shift to higher education, R&D and creative innovation is undertaken. Artificial intelligence and robotics are not a threat, but should contribute to a more sustainable society.

CHAPTER III: ROBOTICS IN THE NEW ERA

To understand new inventions in industrial robots for what they are implies to clearly distinguish innovations from product enhancements or added gadgets. Subsequently I will use an economical modeling tool with defined criteria to evaluate the new innovations in industrial robots and verify their applications. Military robots as a whole – except for UAV - are in still their early development phase, so plausibly their future, its new era, will be filled with all kinds of innovations. This makes analysis and prediction statements arduous. To understand where military in the new era will lead to a thorough understanding of its current limitations could provide answers on areas for future development.

3.1 New applications

Before analyzing the new technological advancements in industrial robots, it serves to look at where robots are being used for the first time, away from the traditional markets and segments. More and more industrial robots are used in industries far away from the original automotive industry. In example slaughterhouses use now industrial robots equipped with vision systems to cut open cows and pigs. Robots positioned on 4x4 trucks are used to position solar panel in deserts and other remote areas. Even the flower industry has embraced robots for high speed planting of seeds. Al these new application fields are based on existing technology and available technology. Industrial robots work mostly in predetermined conditions and closed environments. This covers for the many industrial needs based on large series and repetitiveness. However, take for example the process of building an airplane which is still done mostly manual. In case automation is in used aerospace it consists of dedicated equipment, with low flexibility and high investment costs. In aerospace the series are relatively small, the complexity is high and so is the need for quality and precision. So in essence this is a not so easy task for any industrial robot. The same applies for many medical processes. Medical processes are labor intensive and require a high accuracy and hygienic environment. Question is if standard industrial robots are suitable to work in these environments or if new innovations can make the difference.

3.1.1 Light Weight Medical Robots

Research and development of automating medical processes using robots is growing fast. In the last decades robotics and remote robotics are being introduced into more and more in medical applications. With its high repeatability and arm rigidity the field of surgery has a large potential. It can provide medics with an additional option in how to tackle complicated medical issues. The main benefits can be found in precision, smaller incisions, which mean less pain and side effects [3.1]. Successive healing is then faster, so costly hospital time is reduced and throughput of patients can be increased. The Light Weight Robot surgical robot *MIRO* shown in Figure 32 designed by DLR is a good example of these new applications for robotics. Hagn in [3.2] shows that the developed surgeon robot MIRO, with its integrated torque sensors, light weight design and extended versatility, can be used in the operating theatre for a limited range of of surgical applications. Although robots are inherently flexible and versatile, it does not mean that a robot, like MIRO, can perform all required medical surgery tasks.

Figure 32 .The MIRO surgeon robot [32]

Modularity is part of the solution, as robots become scalable towards the required application, and tuned by parameter settings. In addition, as with any robot, adding dedicated instruments to the robot's universal end effector and adapting its many internal control sensors can achieve the required flexibility.

The future prospects are blooming for this sector. The global market for medical robotics and computer-assisted surgical equipment was worth nearly \$2 billion in 2010 of which 70% in surgical robots alone. The forecasted growth indicates levels of more than 10% per year. Leading geographical area is the U.S., which accounts for more than 2/3 of the global market in 2010 [3.3].

3.1.2 Aerospace and Robotics

Another field where industrial robots are being applied is that of aircraft manufacturing. As the whole assembly and paint process is still done mostly manual, large cost reductions could be achieved if standard industrial robots could be applied. Most parts and components in the aerospace industry are complex and large of size; production volumes are typically low. Also aerospace industry typically requires tighter tolerances, and uses lighter, stronger materials than normal industries like the car industry. Even combined composite materials are used. In 2012, articulated robots are far more affordable than dedicated machinery for the same purpose, while their setup and programming, supported with offline 3d software is relatively easy. Due to the large sizes of the plane assemblies, mobility of the tools is a must. As a result large gantry systems are used in most cases, equipped with dedicated machines and tools. Traditional hard automation consists of quite inflexible machines that need to be replaced with each new aircraft model. So when the aim is to use flexible automation conventional 6 axes articulated robots come into play, positioned on gantries, and/or Light Weight modular robots. The latter being easily mounted on movable platforms and they can work closely to the factory worker. Typical applications in aerospace industry are:

- Drilling;
- Riveting;
- Grinding;
- Polishing;
- Sandblasting;
- Painting;
- Coating.

All these applications are done with robots in other industries. The aerospace requirements defined by payload capacity, rigidity and accuracy could not be handled with standard industrial robots. However industrial robots enhanced with higher calibration and using vision systems and high level off-line programming do reach the stringent aerospace standards. Also a shift in part design needs to take place, as happened in the automotive industry, where parts are designed in such a way that its manufacturing can be automated. The aerospace industry definitely lags behind here. Drilling is a high-volume operation in aerospace, hundreds of thousands of precisely located, straight holes per aircraft. Airbus drills some 50 million holes per year, of which half are done manually [3.4]. And this is just Airbus on drilling. The market potential is therefore massive.

While for the medical sector a new dedicated and affordable robot design has emerged, this has not (yet) occurred in aerospace industry. Current robot manufacturers like FANUC and Kuka merely enhance their standard products to reach the demands set out by the sector. Hence no innovation can be identified.

3.2 New Challenges in Robot Design and Production

The main question that arises is what challenges the current field of industrial robotics that can be applied as a technological innovation? As technology is progressing at exponential rates, so are the possibilities and applications of industrial robots. Kemp et al argue in [3.5] that industrial robots are more successful than mobile and/or service robots because they work in a controlled environment. Without vision systems and sensory interfaces, robots have really no perception of their environment, reducing them to programmable machines with poor added value. So a controlled environment is a prerequisite. By giving robots perceptual systems and tools they can advance in working under random events and undetermined environments. Integrated vision systems are in 2012 already commonplace when it comes to their use together with industrial robots. The added use of force sensing is moving robotics in general, and industrial robotics in specific in newer areas. As industrial robots have been around for 4 decades, since their first introduction their growth has been unstoppable [3.6]. I showed that industrial robots have entered the Maturity Stage of the Product Life Cycle (PLC). So following the logic of the theory behind the PLC the Maturity Stage can be as long as 5 to 30 years and is characterized as a period with few changes on the developed design. The Maturity Stage shows the following characteristics:

- Manufacturers enlarge and streamline production - Producers need to achieve the needed economies of scale to gain competitive price advantage;
- The product does not undergo many more changes;
- The market is characterized by price pressures - Due to still a high number of suppliers (>5) and a homogenous product offer;

- Steady demand;
- High acceptance of the product.

All these characteristics are valid when taking a closer look at the industrial robot. [3.7] Through the introduction of complete new solutions, (like how the memory disks were replaced by USB memory sticks) the current technology can be challenged. But where are the challengers in industrial robot-land? The Maturity Stage is followed by a sharp decline in demand and basically death of the product, see Buzzel [3.8]. Robots will form no exception, and despite the fact that the Decline Phase is still far off, challenges that are putting pressure on the conventional design determine robotics for the new era. The challenges do not come from new products, but can be seen as typical *extensions* on the main curve of the PLC.

Life cycle extensions are made through innovations on the basic developed design of in this case industrial robots like articulated and parallel link robots. These extensions themselves can turn into a new Growth Stage, thus extending the life cycle as a total, see Figure 33. A good analogy is the innovation from the conventional mobile telephone into a smart phone [3.9]. The mobile phone industry entered a complete new growth stint. With no new breakthrough technology emerging, it is exactly here at this point in the PLC where I focus; the new challenges on industrial robot design. It is necessary to establish these new areas that are currently being explored by academics and manufacturers and that have all the possibilities to re-lift the market to an even higher level.

What kind of criteria has to be taken into account to establish whether a new product on the market is a new technology or an innovation based on the basic developed design? In the case of robots for the aerospace industry no new technology was offered but mere add-ons.

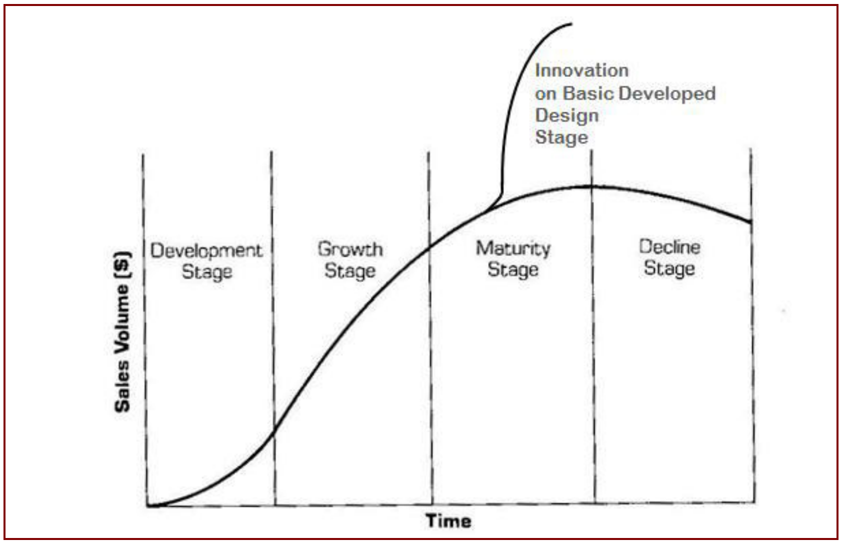


Figure 33. Extended Product Life Cycle [33]

I established the following three criteria to determine whether the actual variations on the industrial robotics market are extensions on the product life cycle or mere product enhancements:

- **Technological Improvement** - The technological improvements have to be on the existing design, not the introduction of a new technology;
- **Market Channel** - The market introduction goes via existing channels, and focuses on the same customer target group;
- **Application Innovation** – The innovation must be recognized as such, it serves a new application or enhances substantially existing applications.

In order to discover the trends in robot design, the next step is to analyze these three criteria against the various innovations that exist in the market place today. When it comes to industrial robots and basic design, they can be divided into 4 main categories: Cartesian Robots, SCARA Robots, Articulated Robots and Delta Robots (also known as parallel link robots) [3.10]. I researched the evolution of industrial robots in these categories over the last 5 years, and among other less challenging innovations, found:

- 6 axis delta robots;
- 7 axis articulated robots;
- Cartesian robot with added 4th axis;

- Dual arm robots using one base frame;
- Hollow wrist 6 axis welding robots;
- Integrated cabling for spot welding robots;
- Lightweight robots;
- Robots using carbon fiber composites;
- Robots with wireless teach pendants connected;
- Service robots;
- Six-axis hybrid kinematics robot;
- Vibration control learning robot;
- Zero footprint SCARA robots.

Matching each of these considered innovations with the criteria as set out to determine whether they are a new innovation based on the developed design and can branch into a new growth phase on the PLC provide 4 new and innovative solutions.

3.2.1 Industrial Robots

These are the following innovations that satisfy all of the three criteria as set in 3.2:

- Light Weight Robots;
- 7 axis Articulated Robots;
- 6 axis Delta Robots;
- Dual arm robots using one frame.

Each of these innovations is positioning industrial robots on a new extended product life cycle path. Certainly the limitations in the traditional basic designs have pushed for these developments. Reachability and flexibility have been the center of industrial robotics. Modular design is in direct conflict with reaching economies of scale through mass production while mobility is in direct conflict with a conditioned environment, a pre-requisite for actual industrial robot. But with the realized benefits of deeper integration of robotics in our factories, the need to position them closer to humans is evident. This requires a fresh look at the conventional design. All of these innovations can be found in the market in 2012. They are in their initial phase of the extended growth path and acceptance.

One group worth mentioning is that of Service Robots (mobile robotics). These robots do not match the stated criteria as they offer a new feature that current industrial robots do not possess, that of autonomous mobility. Also they focus on a different segment, namely domestic use first and foremost and are distributed through different channels to a different segment. Hence I classify service robots as a new product. Service Robots are still in their Development Stage of the PLC. The Service Robots will therefore not be considered at this point. Many manufacturers and universities built prototypes, some with big future potential.

3.2.1.1 Light Weight Robots

Traditional articulated 4 / 6 axis industrial robots base their success on working in an environment that is adapted to their use. They possess a large Return on Investment ROI, often realised within one year. This ROI is realized through the design of robotic cells especially for their purpose, like handling cells, arc-welding cells etc. The repetitiveness achieved in these created surroundings, combined with precision and high quality output form the basis of their success. Cost efficiency of industrial robots is reached through economies of scale; produced en-mass from steel castings they have generally a large weight; albeit a poor weight to payload ratio, they have a high stiffness and can carry large payloads. With a total stock of operational robots world wide of about 1,100,000 robots in 2009 [3.11] the experiences gained by end users in industry are huge, pushing the needs further. Once an end user of robotics has experienced the gains of using flexible automation with robots, as shown by phase I the adaptation rate of robotics growths. Not every environment is equally suitable for flexible automation using robots. The environment can rapidly change, or the series of products to be processed become shorter, or the closeness of humans makes robot automation impossible, due to the safety needed.

Traditional robots do not fit this picture. So Light Weight Robots came into vision beginning of the new century. These are robots, based on traditional 6 axis articulated robots but especially designed for use and placement in unknown environments and possibly mobile. Typical two characteristics that traditional industrial robots, as described above, do not possess. Also Light Weight Robots are designed to interact with humans. Mobility and flexibility require a light-weight design with a high load to weight ratio. Optimally a 1:1 ratio, combined with high speed.

To fulfill the need for flexibility the build typically is modular, with integrated mechanical and electronic design. These light weight robots also have control capabilities and sensory skills for complete interaction.

Figure 34. Light Weight Robot by Universal Robots [34]

The in Figure 34 shown light-weight robot has six degrees of freedom, a load capacity of 5 kg and weight of 18 kg. The load to weight ratio therefore is a sub-optimal 1:3. Further this robot has joint torque sensors in each joint, which are connected through aluminum structures, and a redundant position measurement. Cabling is all within the arm, using fiber optic bus systems. In this way it can sense objects upon touch and react accordingly in a safe manner. In [3.12] Hirzinger et al show that the DLR robot, the prototype on which the Kuka unit is based, is able to detect and distinguish unexpected collisions from an intended cooperation, in which a human stretching out his arm, tries to catch the robot. This provides a “subjective safe feeling”, it is safe because the user interprets the robot behavior as safe. The study showed that the robot inflicted no harm to the operator at any of the considered velocities and it was always possible to detect the collision and let the robot switch to one of the investigated reaction strategies. These Light Weight Robots are used close to or in corporation with humans. Therefore, apart from compliance to international safety standards, the fact that the robot stops at even the lightest touch compensates the intrinsic mistrust, even fear from humans towards intelligent machines [3.13].

3.2.1.2 Articulated Robots with 7 Axis or more

If innovations on the basic developed design extend the life of a product, and even can turn them into a new growth phase, then there is a second group of innovations that qualifies and is worthwhile investigating; the articulated robots with 7 axis. Traditionally articulated robots have 6 degrees of freedom, which allow them to reach any point in space from whatever angle, depending on the position of the point in its work envelop. Although 6 degrees of freedom suffice in most applications, in some specific cases the robot needs to be positioned in a calculated position in order to reach the desired output. By adding a seventh axis, or “elbow”, access to difficult areas is improved substantially. The robot does not need to be in a specific calculated position. This 7-axis design copies human flexibility into industrial articulated robots. The advantages are obvious, as this robot design can save valuable floor space in or near machines. The addition of the 7th axis dramatically increases the freedom of movement around the elbow. Conventional 6 axes articulated robots could just not access all positions unless they are positioned in a specific way. The below shown example shows the robot working ‘around a corner”. It reaches into a very limited space loading and unloading a CNC (Computer Numerical Control) machine tool from a warehouse.

Figure 35. 7-axis articulated robot by Motoman loading a machine center [35]

Another gained benefit of the 7 axis industrial robot is that with this design a programmer can avoid unwanted singularity points by giving multiple posture solutions for the same tool center point. The tool attached to a 7-axis robot, i.e. a welding torch, can remain on the target at the same angle while the robot repositions. These 7-axis robots have been introduced since 5 years only and steadily find their way into the market. The increased flexibility comes at a price, as one has to add another motor, drive, gear, cabling and the design of the arm has to be reconsidered as stiffness comes into play. Main markets for these robots are machine load and unload and arc welding. It is expected that within a 3-year time frame all major robot manufacturers will carry 7-axis articulated robots in their portfolio. Yaskawa of Japan carries these machines as standard, see Figure 35.

3.2.1.3 6-Axis Delta Robots

Delta robots, also known as Parallel Link Robots form the last category in industrial design robotics, its design introduced in the late eighties. This kinematic solution provides a conical or cylindrical work envelope and is most frequently applied to applications where the product again remains in the same plane from pick to place, XYZ [3.14]. Delta robots, given their structure, are used for high-speed handling of lightweight products. Since its introduction in 1999 into the industrial robotics market by Swiss-Swedish manufacturer ABB, the design has not changed. These robots can be found in various markets like food industry, the electronics sector as well as pharmaceutical industry, for high speed Pick & Place of various products and components.

Innovation on the basic design came from an unexpected angle; the marriage of xyz plane using parallel-link technology and the 6 degrees of freedom as used by articulated robots. It was

Figure 36. FANUC 6-axis delta robot [36]

FANUC, the Japanese world leader in robotics launched in 2009 worlds first delta robot with 6 axis and hollow wrist, as displayed in Figure 36. This new innovative design of the delta robot combines the best of both worlds. First, through its traditional parallel-link design it can achieve high speeds for pick & place applications in a large work envelop. Second, by adding drives for axis J4, J5 and J6 the standard delta robot for x, y and z is turned into a six-axis robot. The created hollow wrist can orientate and position (pitch and yaw) products in full special capacity along x,y,z,p,q,r. This is advantageous when a product that is picked up by the robot needs to be positioned in a reoriented manner or when it has to be inserted in i.e. a blister while using a wrist movement for proper insertion. The design by FANUC achieves also a high stiffness of the J4 joint by adding the motors for the wrist in the arms. The drive mechanisms towards the wrist have a constant length, avoiding the maintenance intensive telescopic arms, and hence improve the desired stiffness. Thanks to this design this robot can handle payloads of up to 5 kg, where normal delta robots have difficulties of handling more than 3 kg.

3.2.2 Military Robots

To derive a similar picture regarding military robots in the new era as done for industrial robots is not possible. Except for UAV, most military robots are still in their development phase. Similar to industrial robots, the market for UAV's is expanding at an increasing rate. As these types of robots are mainly military I see a continuing dominance of the US and to a lesser extent European countries. For the other military robots it is hard to predict how, and if they will grow substantially or not in the future. Accumulated data is not (publicly) available. The provided segmentation for military robots does provide a first anchor point to start analyzing. A judgment regarding whether or not a military robot concept will be successful depends on many factors.

- **Proven battlefield success** – What lessons can be learned from active deployment?
- **Use of crossover technologies** – Can experience from related (robot) industries push the development and success?
- **Demand for the robot** – Does the robot fulfill its tasks?
- **Available funding** – Is there enough capital to back the necessary R&D investments?
- **Technical feasibility** – What limits the robot to reach the desired optimum?
- **Robot Acceptance** – Do the users, the military feel 'comfortable' or secure to work with the robot?

As with all new emerging technology, it has its upside and its downside. The experiences of the various assault, prevention and reconnaissance robot types deployed in the Afghanistan and Iraqi wars prove their benefit and hence existence. *DARPA*, the US Defense Advanced Research Project Agency operates with a staggering budget of well over US$ 3.1 billion. DARPA finances projects in Aerospace and Space systems, advanced electronics and technologies, C3 systems, network-centric warfare technology, sensor technology and guidance technology, amongst others. The before mentioned BigDog is a DARPA sponsored project.

To understand the future I analyzed the current developments of the projects that DARPA is working. It reveals that that artificial intelligence is high on their agenda. DARPA's Foundational Machine Intelligence program is supporting research on the foundations of artificial intelligence and machine learning and reasoning. DARPA focuses on techniques that can efficiently process and "understand" massive data streams. Machine processing should generate progressively more sophisticated representations of patterns, invariants, and correlations from military and sensory data inputs. It is clear that this will have far-reaching military implications in potential applications such as (anomaly) detection, (object) recognition, (language) understanding, information retrieval, pattern recognition, robot task learning and automatic metadata extraction from video streams, sensor data, and multi-media objects. [3.15] New algorithms are needed that allow robots or unmanned vehicles to generate and manage their own goals within human-described mission constraints. During my research of publicly accessible sources I found that up to 2012 military assault robots are still (far) away from the by Hollywood presented 1984 "Terminator do-it-all" fighter robot. To understand the future trends and new applications of military robotics it serves to understand what are their limiting factors. Can robots eventually outperform humans?

Futurist Ray Kurzweil (2005) investigated the concept of Technological Singularity, a hypothetical future emergence of an artificial intelligence larger than those of humans [3.16]. Although it is an irrefutable fact that powers of computers and other technologies is doubling every two years (Moore's Law), it does not mean that the point of technological singularity with regards to military robotics will be reached. Yet. Apart from the various complex technical obstacles preventing humanity from developing assault robots on the Terminator level, ethical and legal questions emerge as well as economical ones surrounding the deployment of military robots. Also technical issues are constraining the deployment of full autonomous assault robots in 2012.

It is impossible to get the answers on above posed questions regarding the identified segments of military robots. A first challenge is given next.

3.2.2.1 Military Robots and Ethics

From a political point of view, deployment of robot soldiers, or unmanned weapon systems like UAV makes sense. Human or machine does make a difference. The presence of a UAV flying over non-friendly airspace is seen as less of an infraction of sovereignty than with physical troops deployed on somebody else's territory. Also the capture of a robot, as done by Iran that captured a US drone on February 2012 [3.17] does not provoke the same emotional reactions as if a spy plane was downed and the pilot was captured by Iran. Neither the response of the US was that impacting, as they downplayed the incident. The Black-Hawk incident in Somalia did provoke a costly rescue mission. The failure finally resulted in the withdrawal of the US troops from Somalia. Oddly enough, it is now the UAV that patrol the area. So it makes a great difference if a robot is captured or a human. It is very doubtful that the state of Israel would trade a captured robot for 1,200 prisoners or so. Then again there is the question of advanced technology ending up in the wrong hands.

So the employment of military robots have clear objectives and its successes are proven on the battlefield. So what is holding the military back from converting the traditional army into a robot army? The control or lack of control over machines and its public relations effect are not to be underestimated. One function that robots do not possess is "moral" or ethics. Humans are still driven by a conscious. Ethics are built on values, tradition, religion, and rules. Human soldiers are accountable and protected for their actions under various war conventions, like the Rules of Engagement written in the Geneva and The Hague conventions. It governs what is acceptable and what is not in warfare. Ethics and conventions alike describe the concept of a "Just War".

The following question arises: do or should autonomous (assault) robot follow those same rules? Subsequent question is can robots be programmed according to these rules of war and morality? If I assume that an Assault Robots can operate autonomous then inherently it can make the autonomous call on the use of force, the decision to kill. Small errors in perception (by the robot) can kill innocent civilians and/or can cause unwanted collateral damage. So guidelines and fail-safe systems are needed. On November 26th 2011 the US launched a drone strike in Pakistan, killing 24 Pakistani soldiers, allies of the US. [3.18]. A typical real life example of the risks involved in using unmanned technology, where decisions are made not yet autonomous but far away from the real theatre. It (only) stopped the US for 6 weeks before another Taliban leader was killed by a drone strike in the same region. A 2004 study showed that that human-error plays as significant a role in UAV accidents, approximately 33% in all cases investigated [3.19].

Apart from people using unmanned machines making mistakes, from an ethical point of view, and legally as well, it is important to establish the chain of responsibility in case the machine makes a mistake. If a civilian looks like a terrorist, who determines the order to fire? And who is eventually responsible? In 2007 an automated unmanned anti-aircraft gun killed 9 soldiers in South Africa when some malfunction occurred during a live training exercise [3.20]. Ronald Arkin in [3.21] advocates for military robots to have a moral; they should not always follow orders. It must be possible for the robot to refuse an order, if it is deemed to be unethical. Consequently would commanders than also allow for their soldiers to refuse an order based on personal moral? Basically it means that robots should operate following some ethical software. John Sullins in [3.22] argues that future unmanned Assault Robots should be designed in such a way that human targets should be identified as such and that a moral agent, (human or non-human) is in full control. If no human can be in the loop these weapons should not be used. In addition he argues for operators to receive training in “just war”. Can an assault robot identify a wounded enemy soldier as being wounded and would it refrain from killing him?

Learning from history confirms that the outlook is not that promising. It was the great military philosopher Carl von Clausewitz (1780-1831) who said that, even far before military robots were born, “*the invention of gunpowder and the constant improvement of firearms are enough in themselves to show that the advance of civilization has done nothing practical to alter or deflect* *the impulse to destroy the enemy*". Which is of course the very central idea of war [3.23]. The means justify the ends when it comes to war. It is the ethics of the people running the machines one should worry about, not the machine itself.

Finally remains the question of who defines what is ethical and how to apply it? In the 2009-2034 roadmap of the US Department of Defense on Unmanned Systems [3.24] the word "ethics" is never mentioned, not even once! Humans can invent weapons and robots to kill, but do not bother to debate on the use and responsibility of these systems. Wallach et al in [3.25] suggest that the development of artificial intelligence will contribute to a discipline dedicated to the understanding of how robots make successful moral judgments, which in turn free them to pursue their goals and purposes, in this case the military objectives.

3.2.2.2 Military Robots and Technical Constraints

Looking from a technical point of view at the constraints using military robots some immediate elements come into focus:

- Energy supply;
- Target Discrimination;
- Environmental Complexity.

Energy supply. Human soldiers need food, sleep, water, oxygen etc. and are hence autonomous up to a certain point. It also makes human soldiers vulnerable and their deployment costly. Also humans need clothing and body armor, adding to the overall weight to carry around, reducing battle speed and ammunition supply. Re-supply for humans needs to be found locally or brought in. Robots are less demanding to that effect, but still depend on on-board energy supply to run its motion and weapon systems. Current battery capability is a limiting factor and the more robots are equipped with sensors and weapon system their energy demand will go up. In case of prevention robots and reconnaissance robots this is not a crucial factor. It does become important for assault and logistics Robots as described in the Military Robotics Driver Matrix. With the advancing technology in battery power and the introduction of super conductors (which use only a fraction of power) the energy supply constraints will become less.

It is evident that robots do not need extensive life support or protection as humans do. So design of logistics and assault robots is substantially different than if humans were ‘on-board’. It makes them lighter without these add-ons, reducing weight and hence increasing the weight/energy consumption ratio. UAVs can stay up in the air already many hours continuously without refueling, only enhancing to their functionality. DARPA is currently investigating the development of new thermoelectric materials with the objective to develop new components for use in diverse power systems that will dramatically increase overall energy efficiency. The focus is on new permanent magnetic materials with significantly higher magnetic strength and higher operating temperature for motors and generators, as well as high energy density capacitors [3.26].

The second identified point is that of **Target Discrimination**. To become autonomous implies being able for the robot to act, plan and execute its tasks based on the input from its sensors, its objectives, learning capabilities and programming. UAV are all flown by operators, albeit remotely. Humans execute the targeting and fire control. So UAVs operating in war theatre like Afghanistan are not fully autonomous, albeit technically it is deemed possible.

These weapons fly over non-friendly territory, executing various tasks like reconnaissance and strike missions. The vision recognition technology needs to discriminate combatants from civilians or other. Enemy soldiers like Taliban are known for their disguise tactics, as they are aware of the omnipresent danger posed by UAV. In this case can a UAV tell the difference between a village schoolteacher and a disguised combatant? Is having a weapon on you a just reason for the machine to engage? In many third world countries civilians carry weapons. The robot – or better said the vision recognition software - should be able to read <u>intent</u> based on behavior, facial expressions, body temperature and other tells. Robot implies autonomous function, so the real question is where to put the border where the robot can acquire targets and execute autonomously, if ever.

Also even if the robot detects and 100% identifies a just target, what to do when this target is surrounded by civilians? Again, these are dilemmas, which are currently overcome by the simple but effective procedure of keeping a man-in-the-loop. Again DARPA is working on new systems within their Robust Robotics Program to develop techniques for robots to perform in dynamic environments by improving robotic vision and scene understanding. These systems includes the capability to predict the future location and even the intent of moving objects in order that robots can handle both movement and clutter simultaneously and plan a collision-free course through the environment [3.27]. If frontline troops are going to rely on Logistics Robots they better arrive at the right place at the right time.

The last major identified constraint is the ever-changing **Complexity** of the **Environment**. The wars fought in this decade have not been fought on a classical battlefield, neither in the classical sense nor against classical opponents. Today’s battle terrain can be within dense urban area or remote mountain areas. The enemy is not the classical soldier anymore, but a combatant changing its role from villager to fighter constantly. Identified enemies are driven by various factors like hatred, opposition against occupation, religion, etc. Even civilians take up arms or commit suicide missions. To understand and operate within this complexity is extremely difficult, even for human soldiers. The present danger to our forces comes from IED and suicide attacks, among others, instead of direct classical assaults.

Battlefield automation via robotics should bring answers to these problems and in doing so adding to the already technical complexity of the robots. Because of this complexity the military robots working in the 4 segments of the military driver matrix are remote controlled, by wire or wireless. Only few military robots work truly autonomously. I can conclude that current technical restrictions prevent most military robots from working fully autonomously. As a result most robots have to be controlled remotely, like UAV. The main advantage of operating remote controlled is that it keeps a human in the loop of events. The next generation military robots need to more autonomous and should be able to work together. For this, real-time analysis of the hostile environment and the enemy is necessary. New processing technology is needed for metadata extraction from images and video streams, sensor data, and multi-media objects. This should than be translated for the robots to execute pre-determined objectives within the ever changing frame work.

3.3 Conclusions

Industrial robots keep finding their ways in new areas. Since their introduction they have been a success. Now new innovations on the basic concept for articulated and delta robots allow new growth. Lightweight modular robots have found their start in general industry, medical applications and aerospace manufacturing. By adding more degrees of freedom, a 7^{th} axis in the case of articulated robots and the addition of a wrist to delta robots, a new range of applications is being fulfilled by using these innovations on the conventional robots. Dual arm robots complete the set of new growth areas for industrial robotics in the new era. Design follows function. In general, all robots should contribute to a more sustainable society. More and more robots will become more capable of replacing humans, and by adding vision and force sensing they get eyes and touch. Still human workers will be needed, whether in industry, medical or aerospace manufacture. Their involvement will be different though.

Military robots are here to stay. Their success is proven on recent battlefields like the wars in Afghanistan and Iraq (2002-2012). They prevent loss of human lives while doing so in some cases quite efficiently and cost effective. From the “Military Robotics Driver Matrix” reveals that the objectives for these robots are economic and humanistic or a given scaled combination of these two factors. The industry for military robotics is growing, and will continue to grow pushed by national and geopolitical interests. Constraints currently exist and will determine the future development challenges for military robots. Technical issues like energy supply and suitable algorithms for vision target recognition and motion over unknown terrain prevent full autonomy in 2012. The biggest constraint is perhaps the ethical issue on the use of Assault Robots. These robots can work in the future autonomously from a technical viewpoint but probably shouldn’t as they do not operate from a moral point of view. The military robots in operation in 2012 are mostly are remote controlled and hence have a man-in-the-loop. A weak point, if considering that machines are faster and more intelligent. But the human factor brings the needed moral anchor. Tomorrow’s military technology can let assault robots work autonomously. It is a matter of time before algorithms and smart software combined with new fast computing hardware makes this possible. The robots should be equipped with some sort of moral intelligence. A military robot that kills indiscriminately like landmines or biochemical agents is in general morally rejected.

CHAPTER IV: A New Understanding of Modern Robotics

The industrial robot has not changed its architecture much over the last 30 years. It still consists of high performance joints powered by servomotors and linked by reducers, converting it into a flexible manipulator. I aim to identify key topics, and challenge problems that are likely to shape the field of robotics in the near future. As stated in chapter 2.2 the goal of using robots is to gain a competitive manufacturing advantage. Cooperation of robots and humans together on the workplace is the final step in achieving flexible assembly using robots. The ultimate goal is to have a flexible and dynamic production environment where robots and humans work literally hand in hand.

4.1 A New Understanding of Modern Robotics

The question arises of why robots and humans don't cooperate so far? In general, industrial robots harbor a high risk of injury for human operators when they are in proximity of a working robot. The main dangers identified are:

- Impact with a large mass moving at a high relative velocity;
- Encountering with opposing movements;
- Possible pinching of man between robot and its peripherals.

Oberer in [4.1] identified considering three layers of robot safety for specific robot systems:

Sub-layer: **Performance Control**, i.e. safety related control functions to limit specific performance parameters by the robot controller.

Mid-layer: **Active Safety,** i.e. collision avoidance due to intelligent processing of environmental information (workspace monitoring by sensors)

Top-layer: **Passive Safety**, i.e. means to reduce effects in case of a collision (crashworthiness)

As the current industrial robots are not designed to the above mentioned passive safety criteria, the solution has been so far to remove the human operator away from the robot by placing the latter in an exclusive safety zone. Hard fencing, safety doors, light barriers, pressure mats, security locks and dual chain circuits are all active safety measures implemented with the goal of keeping the human operator out of harms way. By keeping the robot and operator separated an implicit limitation was created with respect to the possible applications and benefits of industrial robots. It was just impossible to automate complex assembly work due to the ergonomic constraints of having human operators working near robots.

In order to derive conclusions on the design philosophy of industrial robots it is paramount to understand what factors drive the robot design in order to reach the ultimate objectives with respect to flexible automation? Considering a fully automated factory where robots and human operators freely cooperate as the ultimate level, it fulfills two main two scalable main drivers:

- Production Flexibility. The level of flexible automation, reaching the highest phase IV (see Figure 37);
- Assembly Complexity. The level of task complexity achieved.

These two drivers can be combined to group industrial automation on the two identified scales. This Automation Matrix uses the degree of flexibility needed in the production process - by considering full automation as the ultimate goal - and the complexity of the assembly process. The terms ‘assembly’ contains also other manufacturing tasks like handling, de-burring, joining. Figure 37 shows the Automation Matrix.

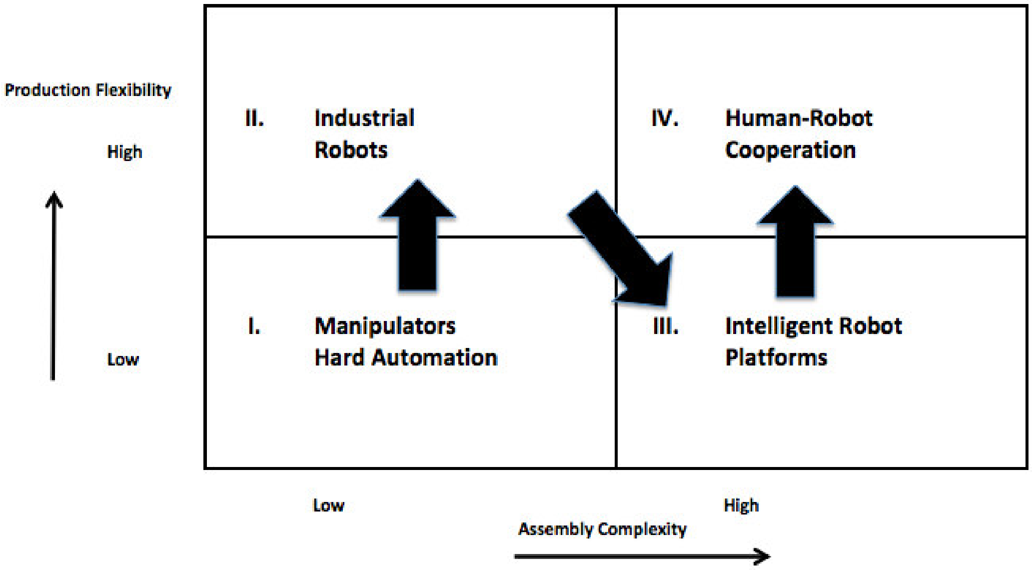


Figure 37. Automation Matrix [37]

Traditional automation started in the first quadrant; where no real level of flexibility is achieved and the assembly complexity is low. Traditional automation equipment like pneumatic cylinders, bowl feeders, conveyors, xyz manipulators for handling can be named. These machines were in fact the first approach in bringing some form of automation to the production process. This basic form of automation still represents the bulk of automation integration in most factories.

With the installation of the Unimate, the first operational industrial robot in 1961, the way was opened to reach much higher levels of production flexibility. Flexible automation using industrial robots are used to gain a high level of flexibility in the work process while still working on the basic low level complexity in assembly. All normal typical industrial robot operations like spot and arc welding, handling, palletizing, pick and place, load unload provide a high flexibility to factories while handling large batch series. Industrial robots in segment II support processes, which are not complex from a robot point of view. The needed complexity is brought forward to the tools attached to the robot or to the machine, which the robot is tending. Some 90-95% of all industrial robots can be found in segment II.

Starting with the new millennium a new step forward was made to use standard industrial robots for complex assembly processes. A shift to higher assembly complexity was created, in the driver matrix from segment II to segment III. This step was realized by making the robots ‘intelligent’, by upgrading the robot from a mere reproducer of a stored program to an intelligent machine. The added ’intelligence’ allows fulfilling assembly processes with a much higher degree of complexity. Two main elements of this added intelligence can be recognized:

- 2 and/or 3 dimensional vision systems. To give the robot eyes;
- Force sensors. To give the robot feel.

The last decade industrial robots are being equipped with these technologies. It allowed the industrial robot to penetrate complex assembly processes, albeit only realizing a low production flexibility level. Embedded vision systems were first used for location positioning and orientation determination to be able to pick (up) parts. Later, vision systems were applied for more advanced applications like inspection. Force sensors added to the robot allow the robot to deviate from the programmed path in order to assemble high precision parts or work on a part with a constant force. In 2011 some 10-15% of all industrial robots are equipped with a vision system. Less than 1% is equipped with a force sensor. So by adding intelligence to the standard design more complex assembly is reachable, but not high production flexibility. Why not? The technical factors limit the effectiveness of these intelligent robots, these technologies are:

- not suitable to handle or all materials;
- not suitable to work in all environments. Changing lighting and /or temperature condition can not be supported;
- not economically interesting due to the relative long cycle time needed by this technology.

So intelligent robots can now see and feel, but are still limited in their application. Even more, they still need high safety measures to protect workers from bodily harm when working with them.

To reach the form of maximum flexibility, the combination of complex assembly systems with high flexibility in the production process, an adaptive production system is needed for maximum efficiency. In this segment IV short batches and high variations are the norm. Cooperation between human operators and robots create the ‘perfect’ marriage between man and machine. An example is given in Figure 38. In quadrant IV industrial robots and humans literally work hand in hand. Both handle sub-assembly parts and share work pieces. Also mobile robots can bring parts to human operators for further assembly or inspection. Humans and robots share here the same workspace without hindrance of physical safety barriers. This production model uses human capital and robots both in their optimal way. Lacevic [4.2] proposes the use of rapidly exploring random trees paradigm to establish a collision-free path for robot arms in a configured workspace. The goal is to let humans work flexible in highly complex and fast changing assembly processes while robots endorse their payload, precision and repeatability.

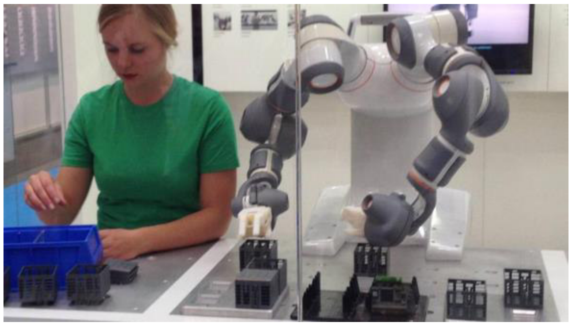


Figure 38. Human-Robot cooperation [38]

4.2 New Robot Design

The robots suitable for quadrant 4 of the Automation Matrix of Figure 37 differ conceptually from traditional industrial robots. To use robots near human operators implies the robots to cause only a low admissible risk of injury at the most. To make this possible force sensing in each axis or sensor guided robotic systems are needed combined with low forces and moments. The investigated data shows that its core design is often based on the dual arm principle. Analyzing data provided by manufacturers [4.3] [4.4] [4.5] [4.6] of these new robot models show that the following characteristics for these new industrial robots are mandatory:

- Light weight design;
- Dual arm, 14 DoF (Degrees of Freedom);
- Torque force control actuators;
- Easy adaptive teaching;
- Low power Consumption.

Using these new generation lightweight robots allows humans to work side by side or face to face with them, without safety barriers. The robots are programmed via Interactive Learning. Because the workplace system design based on the manufacturing requirements is complex, so are the interactions between humans and robots. According to Goodrich [4.7] it is impossible to anticipate every conceivable problem and generate scripted responses, or anticipate every conceivable percept and generate sensor-processing algorithms. Interactive learning is the process by which a robot and a human work together to incrementally improve perceptual ability, autonomy, and interaction.

4.2.1 Light Weight Design

As stated in the introduction, the main problem with current industrial robots is its multiple sources of hazards to human operators and or peripherals. Industrial robots are designed to work under heavy duty using a high cycle. They move at high speed (above 1.5 m/s) and move a considerable amount of body mass plus payload. Even a standard mini-robot with a maximum payload of 5 kg still has a body weight of 32 kg and can move at 2 m/s. Current industrial robots are capable of destroying itself, grippers, peripherals and can harm or kill human operators.

The use of lightweight materials such as plastics and aluminum bring the body mass down considerably. A logic consequence of the reduced weight is that the motors needed to drive the joints can be of reduced size. A ‘negative’ consequence is that the available payload is also reduced. Besides reducing hazardous collisions they reduce the energy footprint. Another benefit of the reduced weight is that these robots do not need any more a sturdy base to compensate for the high moments that occur when the robot halts in case of an emergency stop. They can be easily mounted on light structures or even mobile platforms to perform different tasks at different locations. Below Figure 39 shows the current lightweight robots available.

Robot type	**Number of Arms**	**Payload in kg**	**DOF**	**Weight in kg**	**Power Consumption, in W**
Universal Robot	1	5	6	18	200
Kawada NextAge	2	2 x 1.5	15	28	1,500
ABB Frida	2	2 x 0,5	14	20	n/a
Kuka LWR 4+	1	7	7	16	n/a

Figure 39. Light Weight Robots overview [39]

4.2.2 Dual Arm Concept

Although the Universal robot and the Kuka robot are not designed standard as Dual Arm, they can be used as such without limitations. The dual arm concept allows the robot (torso and two arms) to copy work processes by humans. The two hands can work together in multi motion or can work separately from each other. Especially at SME’s where there is no robot experience, the first steps of automation with robots will be to replace a human task by a robot task, mimicking the tasks and procedure (phase 1). Dual arm robots have only one central processor so it is relatively easy to program, as the central unit knows where its arms are and automatically avoids inter-arm collision. In most cases 7 DoF per arm is used to provide the arm with a kinematic redundancy. It allows the arm to position itself, taking a pose as it were, independent from the TCP (tool center point). A great advantage when working in narrow spaces, or when obstructions do not allow access with a traditional 6-axis robot. Figure 40 below illustrates an example of a dual arm robot.

Figure 40. Dual Arm concept 'Next Age' in an aeronautics assembly operation [40]

Robot surface design is smooth and curved, added with soft patching at critical areas to avoid hazardous pinch points for humans while interacting in the same workplace. The big benefit is in the interaction, where robots physically can hand over parts or tools in a safe and controlled manner to humans. It is in fact the next revolution in robotics, where two distinct worlds come together. Summarized benefits of sensor controlled lightweight dual arm robots over traditional 6 axes articulated robots are:

- Safe interaction with humans is possible;
- Multi arm use or single but from 1 robot controller;
- Can operate as a human, having 2 arms;
- Kinematic redundant, obstacle avoidance and pose selection;
- Safe Arm Design in case of unwanted collisions.

According to Rocco [4.8] the dual arm robots must operate under the Self-Collision avoidance principle when it comes to Safety-oriented path planning. The industrial lightweight robot designed by Universal Robots (Figure 34) is the first robot to cross over directly from quadrant II to quadrant IV, as they can be used under limited circumstances next to humans without additional safety.

4.2.3 Torque Force Control Actuators

It is obvious that when robots and humans share the workplace and collaborate in a cooperative manner new rules on collision are needed. With current industrial robots when humans enter a work cell or approach a robot the latter is switched off via dual chain (active safety) circuits. This provided absolute safety but does not allow for human-robot cooperation. So instead of fences, safety doors and light barriers new technology is needed to protect humans from injury and/or harm. Sensor technology like torque sensors in lightweight robot arms (Universal Robot and LWR4+) and adaptive cognitive vision recognition systems are needed. In the case of Frida from ABB a method of doing force control without a force sensor is used. The method is based on detuning of the low-level joint control loops, and the force is estimated from the control error. It has been experimentally verified in a small assembly task. [4.9].

When the robot touches the human or a fixture a fundamental distinction must be made between collisions and a ‘normal’ or even desired contact. The latest standards concerning robot collisions permit only collisions that cause slight injuries to skin and bruising to the underlying tissue. The injury can vary per body part. The robots listed in Figure 39 all carry torque force control sensors on each joint. It allows for easy position detection and referencing of parts. Any tasks related to force control like joining and assembly is now within easy reach of these lightweight robots. Collisions are measured per axis and the robot control determines whether to stop or interact with the human or peripheral. New algorithms will determine the process flow. By making the robot sensitive in all its axis there is no more need for sensitive in the robot tool. Instead, by using tool exchange various simple tools can now be used to perform tasks that before were considered difficult when using traditional industrial robots.

4.2.4 Easy Adaptive Teaching

Industrial robots are flexible and freely programmable for the most difficult tasks. But here lies the root of the problem; a minimum degree of robot programming experience is needed (minimum course 5 days for a novel user) while most factory operators do not posses these skills. Also when dealing with short batches and large product variances, or when the robot is used in many different locations this becomes a costly affair. While in the automobile industry robots have been around for more than 4 decades, in most SME this is not the case. Nor do SME have automation departments like those that can be found in the automobile industry. Traditional robot teaching is done manual by jogging the robot. The programming is done either via text or icons, or via graphical off-line programming software. In either case it is a tedious and difficult task. The new generation light weight robots, having torque force control sensors in each joint, can be programmed by just moving the robot hand manually and record its path and start and end points, lead through or PbD (Programming by Demonstration). This kind of intuitive and adaptive teaching enables non-robotics operators to work with this technology. Using PbD to program the robot, no specialists are needed in set-up or operation. It also becomes much easier to re-program the robot when a production line is changed. Calinon et al in [4.10] propose a method to extract the important features of a PbD task, then to determine a generic metric to evaluate the robot's imitative performance, and finally to optimize the robot's reproduction of the task, according to the metric of imitation performance and when placed in a new context. Although the earliest robots in the ‘60s started with this kind of teaching, it has been abandoned and in 2012 adaptive teaching is still in its infant phase. Also robot manufacturers use their own high level teaching language as there is still no common format agreed among the manufacturers.

4.2.5 Low Power Consumption

Having a lightweight design, using materials like plastic and aluminum reduces the weight of the robot arm and hence the need for powerful motors. The power consumption, see Figure 39, can be reduced to a minimum of 200 W in case of the Universal robot arm. The energy footprint is reduced, but more important it allows these robots to be used mobile. Especially in assembly tasks with high variation the robot can be moved from location A to location B without need for heavy frames. The robot can be moved on a guided movable platform. Battery driven operation is possible. Also, due to the low power consumption, collisions are less harmful and make the robot safer. Summarized benefits over traditional 6 axes articulated robots are:

- Less energy consumption;
- Mobile operation possible;
- Easy installation;
- Less energy release at collision.

All these factors shorten the payback time of the robot versus a traditional industrial robot.

4.3. Adaptation of the Workplace

With the entry of robots in quadrant number 4 of the Automation Matrix, see Figure 37, it is possible to use robots in the many small and medium sized enterprises (SME) where no high level knowledge base for automation exists. It requires from the robot systems a new approach for easy set-up and teaching. Pricing for robots have decreased over time, and so has the technological threshold for programming. However SME's typically do not have the financial capabilities to constantly re-invest in expensive system set-up and programming by 3rd parties. As analyzed in [3.4] the adaptive teaching is a step forward in bringing the new generation robots into the high complexity assembly process. To become fully flexible, the workplace needs to be reorganized to enable fully the optimization between man and machine. And a reshaped workplace requires new norms. The current safety standard for robots in the workplace, ISO 13849-1 is currently being rewritten. The old norm is to be replaced by ISO 10218-1/2 and ISO 15066 which determine the way humans and robots can work together [4.11]. A 3D vision recognition integration system will enable future operators to interact with the robots in a different way. Voice commands and pre-defined hand gestures instead of automated PLC control determine the interaction with the robot. According to Ueno [4.12] vision-based gesture recognition systems can be divided into three main components:

- Image processing or extracting important clues (hand shape and position, face or head position, etc.);
- Tracking the gesture features (related position or motion of face or hand poses);
- Gesture interpretation (based on collected information that support predefined meaningful gesture).

Face and gesture recognition simultaneously will help in future to develop person specific and secure human-robot interface. By having the workplace equipped with gesture, pose and intent monitoring vision systems, (similar like to be found on a simple Xbox PlayStation) working with visible light a new dimension is added. These cognitive vision systems can mark i.e. on the floor a safeguarded area making it clear for operators what is safe and what isn't. Any intrusion in unsafe areas will result in a system halt due to its interrupted projection beams. In addition robot status or other production information can be projected in any part of the workspace to provide further information to the user.

Figure 41 demonstrates the use of a hand gesture to stop a lightweight robot movement based on input by a 3D cognitive vision system.

Figure 41. New Human-Robot workplace interface [41]

The new-shared workplaces need to be equipped with these sensor systems to allow reducing robot speed and enhancing safety conditions when a human operator enters a cell, or approaches a working robot arm. Methods and algorithms to track humans, and evenly important, to predict intent of humans within the work cell will be needed to allow full efficiency of the system. Summarized points of future requirements regarding the workplace:

- Command and control via pre defined gestures and/or voice;
- Display of safety zones, status and other production information in the workplace;
- Adaptive Vision Recognition of human intent;
- Characterization of collision potential of robots according to biomechanical thresholds.

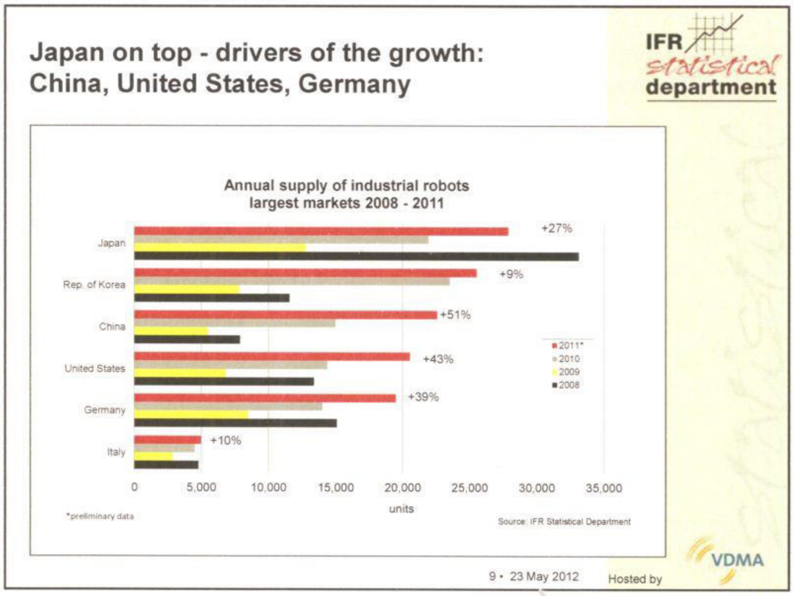
4.4 Economics of the New Robot Design

In the Automation Matrix of Figure 37 90-95% of the industrial robots are in the 2nd quadrant, so the types of industry related to this segment are relevant to analyze. The biggest sector is the automotive industry, where the large OEM and their Tier1 and Tier 2 suppliers can be found. Together they have a share of approximately 60%. The remainder is found in the Metal and

Electronic markets, as well as Food & Beverage and Plastics. Despite the financial and economic crisis that started in 2008 the worldwide use of industrial robots is ever growing.

The conclusions to be drawn from the growth results are clear. According to the latest data in 2011 worldwide more than 165,000 industrial robots were sold. This is by far the highest number ever recorded in the history of the industrial robot. What is evenly important is that this staggering number represents a 37% growth over the 2010 numbers. [4.13] With many countries still exposed to the effects of the crisis, this growth of the use of industrial robots has exceeded by far previous expectations.

What is more is that all geographic regions have peak levels sales, see Figure 42. Not surprisingly, there have been enormous growth rates realized by China (+51%). China is now the 3rd largest user of industrial robots with 22,000 units, only to be surpassed by Japan and Korea (28,000 and 25,500 units respectively). With these growth rates China will surpass Japan by 2014 to become the new number one robot market. In the Americas (+53%) growth has been generated mainly by the US automotive industry. In the more traditional markets like Europe I can see a growth in 2011 by 40% to 42,000 units, with Germany taking the lion share of 19,000 units, a +39% growth. Upcoming markets like Brazil and India confirm their acceptance of flexible automation for future growth by their increased usage of robots.



Japan on top - drivers of the growth: China, United States, Germany

Annual supply of industrial robots largest markets 2008 - 2011

*preliminary data

Source: IFR Statistical Department

9 • 23 May 2012

Figure 42. Annual supply of industrial robots [42]

The main segment driver for the growth in 2011 was the automotive market with 54,000 units, representing a 33% of the total market. Strong investments worldwide made by the automotive sector boosted this growth of 20,000 units in 1 year. The automotive sector is continuously modernizing its production processes. Flexible automation is widely accepted and the norm in this sector. In addition the automotive sector is increasing its production capacity in emerging markets like India, Brazil and China. The growth however is not only driven by automotive. I do distinguish substantial growth in the metal and electronics market. Surprisingly, the Food sector has not grown significantly.

The objective to use robots hasn't changed; to offset rising labor costs, in some regions labor shortage and to increase productivity. These 3 main factors remain the key to success of flexible automation. Also the increased need for high quality output and environmental manufacturing, using sustainable platforms and materials is gaining importance. The new generation robots, in quadrant 4 of the automation matrix where robots work directly with humans are a new sector. This is a new market segment, which comes on top of the existing 165,000 units per year, which occupies the 95% in quadrant 2 (industrial robots) and in small degree (5%) in quadrant 3 (intelligent robots). To estimate its market size a further segmentation and thorough analysis of quadrant 4 is needed. Besides large industries the human-robot collaboration segment makes the entry to the SME attractive. A definition of what kind of assembly tasks that could typically be carried out by these lightweight robots crossed over the various sectors is involved. The most obvious sectors are:

- Electronics assembly (televisions, tablets, mobile phones, toys, computers etc.);
- Fine mechanical parts assembly in metal (pumps, gears, watches, industrial mechanical subcomponents);
- Automotive supply (tier-1 products which involve complex assembly).

These are huge sectors spanning across the globe. Countries like Japan, China, Korea, the US and Germany could benefit highly when the human-robot collaborating types enter the market place. A first estimation leads to a volume of 100,000 units per year. In Europe this would include the many SME's that now forsake flexible automation due to its high economical barrier to entry and the typical low planning horizon of these companies.

4.5 Conclusions

Traditional industrial robots have been and are still a key factor in flexible automation and this sector keeps growing fast. The existing robots work in separated safety zones where human presence is excluded. Current interface between robots and humans is hence limited. Despite efforts to move into high complexity assembly (quadrant 4 of the matrix) using added intelligence, a major breakthrough has not been achieved with the traditional design of industrial robots. The new generation lightweight robots, single or dual arm, are intrinsically safe to work with humans and so open up a complete new market segment. This new design philosophy must be supported by clear safety norms and regulations. Such a requirement is not yet fulfilled by the industry. So not only functionality shape new design so does regulation. Using lightweight materials in the design enables the robots to be mobile or to be moved round easily. This is yet another noteworthy difference between current industrial robots, which operate in general from a fixed position. In addition the human-robot collaboration segment robots need to allow for adaptive teaching, a requirement to enter the huge market of SME's. Human-robot collaboration entails also a different human-machine interface. A redesign of the workplace where 3d camera systems can track human presence and intent, and where humans can interact with the robots using predefined gestures are identified. The market size for these new robots is sizable and attractive as it is a new segment untapped by current available robots. The segment of human-robot collaboration can benefit from the already high acceptance rate of normal industrial robots.

SUMMARISED CONCLUSIONS

Industrial robots are tools to transform the manufacturing strengths of companies, industries, countries and regions. It allows sustainable economic growth, partly offsets aging related problems and can create jobs. While current industrial robots are only in 10% capable of sensing their environment, the entry into the human-robot collaboration segment will be a paradigm shift in the world of flexible automation. The aging industrialized societies face an additional challenge on remaining competitive and robotics, especially human-robot collaboration, is the key to its solution. Workspace sharing between humans and robots will transform our factories and manufacturing.

Industrial robots continue their advance throughout industries worldwide. While in the past they were mostly used in automotive related industries, in 2012 new branches like food, medical and aeronautics and SME are opening up. With these sectors come the demand of having robots respond to an even higher degree of flexibility to overcome the new applications and need to handle shorter production batches and higher change overs. With the many inexperienced users in these new industries and sectors new robot design in terms of application and form need to address the barriers.

Now new innovations on the basic concept for articulated and delta robots allow also for new growth. Lightweight modular robots have found their start in general industry, medical applications and aerospace manufacturing. By adding more degrees of freedom, a 7th axis in the case of articulated robots and the addition of a wrist to delta robots, a new range of applications is being fulfilled by using these innovations on the conventional robots. Dual arm robots complete the set of new growth areas for industrial robotics in the new era. Design follows function.

R&D Investments in automation can improve a countries competitive position while remaining a high cost country, like Germany. China’s star is rising, with large growth numbers in investments, robot density, but is also facing the growing share of elderly. It is to be expected that China will equal Japan in the future when it comes to yearly installed robots. China has no own robot manufacturing but indications show that in the near future this is likely.

Although fear for robots exists, society should fear more the social and economic impacts that this expanding growth of robotics will bring. Unemployment can rise to enormous heights, and lead to an unsustainable social model where large part of human society cannot participate in the capitalistic model anymore, as there will be a surplus of human labor. The welfare of the people comes under attack if no shift to higher education, R&D and creative innovation is undertaken. Artificial intelligence and robotics are not a threat, but should contribute to a more sustainable society.

As sensing and perception of its environment is crucial in human-robot cooperation, a focus on the workplace and human-robot interface must be addressed. Not only from a mere standardisation viewpoint but also with regards to the way the robot is programmed and interacts with its human operator counterpart. Adaptive learning plays a key role in this development. Single or dual arm lightweight robots will be used in close cooperation with humans. Such robots produce high productivity output while working on high complex assembly tasks. Major elements identified are: low power consumption, low weight and modular build, torque sensing or error compensation to allow controlled collisions with human operators, 7 or 14 DoF. Adaptive learning as a way to program the robot will allow entering a new mass market. To reach maximum output in this new segment a focus on robot hardware design is not sufficient. The following areas need to be addressed: co-design of the workplace and in specific the way the human operator interacts with the robot. Body gestures, intent, voice commands are to be included. Standardization on programming language and safety related issues become a priority with the development of human-robot interaction automation.

The “Military Robotics Driver Matrix” proves that the objectives for these robots are economic and humanistic or a given scaled combination of these two factors. The industry for military robotics is growing, and will continue to grow pushed by national and geopolitical interests. Military robots will follow a similar growth path as their industrial cousins, but will take less time to reach the same level. Here proper segmentation will serve as a start point for gathering data. Depending on their impact on human cost and or impact on an economic benefit all military robots can be classified as: logistics robot, reconnaissance robot, prevention robot and assault robots. Military prevention robots have a larger history coming from the de-mining area and find attention in academic circles. The logistic and reconnaissance robots are becoming a new growing segment. The steady growth of UAV deployment will continue and will lead the way to acceptance of other military robotics. Constraints currently exist and will determine the future development challenges for military robots. Technical issues like energy supply and suitable algorithms for vision target recognition and motion over unknown terrain prevent full autonomy in 2012. Aside from technical constraints is the fact that autonomous use of Assault Robots is not possible. Assault robots can work in the future autonomously from a technical viewpoint but probably should not as they do not operate from any moral point of view. The military robots in operation in 2012 are mostly are remote controlled and hence have a man-in-the-loop. This human factor brings the morality that the machine lacks. My analysis showed that there is concern among society surrounding this fact, but no steady answers are available. Assault robots should be equipped with some sort of moral intelligence or rules of engagement.

NEW SCIENTIFIC RESULTS

The new scientific results of my dissertation are the next:

1. I examined and analyzed the types of industrial and military robots used worldwide, and with this basis, I proved based on economic modeling that industrial robots will continue their growth despite their maturity status.

2. I proved the viability of new developments like 7 axis articulated robots, 14 axis dual arm robots and Light Weight robots as they create new growth areas within the Product Life Cycle.

3. I researched the negative attitudes and concerns about the use of robots and the human fear for machines. These fears and attitudes can be overcome by a push in R&D, creative innovation and focus on higher education.

4. I analyzed the impact of using industrial robots on labor. I proved that there is indeed a negative impact on the manufacturing share, but not a significant impact on total labor, disclaiming popular Luddite's theorem.

5. I designed a framework for industrial robots to understand their evolution. I systematized them according to production flexibility and assembly complexity. It highlights the emergence of a whole new sector for industrial robots.

6. I determined that for the human-robot collaboration segment a mere focus on robot hardware design is not sufficient. Enhanced robot functionality itself is not enough to fully benefit from the efficiency possibilities if the workplace and interaction are not taken into account. Essential is the co-design of the workplace and robots. In addition the way in which the human operator interacts with the robot is relevant. I determined that body gestures, intent, voice commands are to be included.

7. I concluded that standardization on the programming language and safety related issues become a priority with the development of human-robot collaboration automation.

8. I analyzed the currently deployed military robots, based on their manifold objectives. I

systematized them according to their level of impact on the human and economic side. Through the Military Robotics Driver Matrix I developed a workable classification for military robots. The designed model can be used for trend evaluation, limits evaluation and can be applied in further academic research surrounding the topic.

9. I analyzed the position of military robots in society. I determined it to be ‘acceptance’ as a direct consequence of the industrial progress and positive experiences of military robots in the latest war theatres. I concluded that military robots would follow a similar growth path as industrial robots, albeit accelerated.

10. I analyzed the constraints on military robots, combined with the experiences gained over time with industrial robots.

11. I have determined some basic requirements concerning the technical necessities that will drive the future design of military robots.

12. I have determined that the ethical aspects of future military assault robots is a concern that needs to be tackled if full autonomous deployment is pursued.

PRACTICAL AVAILABILITY OF THE NEW SCIENTIFIC RESULT

The thoughts and results of my dissertation can be used both in the theoretical and practical phases of both academic research programs and industrial development for military and industrial robots.

The researched issues can affect the design and functionality of future robotics systems, targeted in new innovative sectors like close human-robot cooperation and military (assault) robots. The data supports the following related topics.

- **Market attractiveness for human-robot collaboration;**

In February 2014 the IFR International Federation of Robotics reported that the global demand for industrial robots reached a new high level of some 168,000 units in 2013. This represents a 5% growth over the maximum reached in the year 2012. Most markets have shown growth, like in North America, and due to strong demand in China and South Korea. Europe lagged behind in growth due to the non-existent European GDP growth in the first part of the year 2013. Only the last quarter of 2013 has seen a push in European robot demand, mainly due to the improved economic situation in a key country like Germany. The strong growth of industrial robots in China confirms the analysis of the dissertation. Although a number of factors contributed to the growth in 2012 and 2013, the consistent adaptation of new technologies makes the implementation of industrial robots easier and wider. Part of the growth was realized by introduction of robots in the human-robot collaboration segment. Danish manufacturer Universal Robot has sold more than 1,000 units just in 2013. A small number on the total scale, but significant as these robots can be used in the fourth quadrant of the automation matrix (Figure 37). Another practical example of a start-up company in the 4th quadrant of the automation matrix is Rethink Robotics. This US based company launched “Baxter”, a dual-armed, touch-screen faced robot that can be easily programmed new tasks, and more importantly, work alongside humans without the risk of inflicting injury. The robot is based on a dual arm principle; it has the prescribed 2x7 degrees of freedom and is equipped with a 360-degree sonar. It includes a front camera for vision based applications and sensor operation. The software runs on ROS, the academic born global Robot Operating System. In 2013 Rethink upgraded Baxter's operating software along the lines as described in chapter 4. It now allows academic users to make and create their own applications. The start of an open platform, much like apps on the smart phone as we know them today. It has a software development kit that allows academic researchers and end users alike to work on human-robot collaboration and robot adaptation to changes in its environment and arm trajectory planning. Both the successful Universal Robot and Rethink Robotics examples point to the continuous exploration of the 4th segment of the automation matrix. In the highly competitive market for industrial robots these two start-up companies have created momentum and are in front of the traditional suppliers, their survival and added value clearly anchored within the boundaries of the 4th segment. Both are pushing further in the development of the field of human robot collaboration. In addition, Rethink having an open source product and using ROS as a developer program, will benefit from a swift market adaptation and will pull further application development of the basic product.

A 2013 study on Safety Issues in Human-Robot Interactions by Vasic and Billard underline the necessary safety aspects of overcoming the limitations of human robot collaboration. They advocate that with robots operating in the fourth quadrant, have a higher degree of complexity in robot motion range that will make it more difficult for humans to predict the robot's displacement. Thus the needs for adapted safety aspects become more stringent. It stresses the need for new sensing technology and fast sensor fusion algorithms, as outlined in chapter 4.2.3. Humans can move unpredictable, and while humans are in the presence of a robot, the latter needs to track and sense these trajectories to prevent pinch points and or collisions.

The 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) held on November 3-7th, 2013 in Tokyo, Japan underscored the necessity for collision avoidance in real time when humans and robots cooperate. It promotes the concept of having collaboration with the robot, by for example a hand touching a gripper, while all other objects around the robot are determined unsafe and are considered obstacles. It is with these kinds of approaches that human robot collaboration needs to define adequate safety regulations. On the 2013 IEEE International Conference on Robotics and Automation (ICRA) in Karlsruhe, Germany on May 6-10th, 2013 a proposal was launched to use high-pass and low-pass filtering of motor currents caused by the joint position and velocity of the motors to distinguish between accidental hard collisions and intentional soft contacts between the human and a robot. Safety is derived from the response to a detected intentional contact – where human and robot cooperate. An operator can for example move the robot manually, by pushing or pulling. As laid out in chapter 4.3 the conference pushes the ideas of using exteroceptive sensors (for example Kinect type 3d cameras) and their integration with basic collision detection and follow-up strategies. These types of cameras can easily intercept the movement of body parts of operators working with a collaborative robot

In 2013 the European union launched a program to support the European automotive industry with a low cost robot co-worker (Locobot). It aims to develop a flexible robotic assistant platform to support manual production processes and increase the productivity. In line with the requirements as described in chapter 4, the Locobot aims to develop a Plug & Produce modular robotic platform that uses adaptive control and with modules for sensing and actuating capabilities. The system comprises of rotational conventional cameras to keep the operator in their vision field. These cameras can be used to register gesture recognition and depth information on the work place. This human robot gesture based interaction is still in its infancy stage, where gestures have to be understandable so that the robot can minimize different interpretations. Tracking of human operators can be handled by using an omni-directional camera with 360 degrees view of the surroundings. Typically these type of cameras offer a resolution less important than conventional ones, but sufficient for tracking purposes. The system also carries 8 directional microphones for speech recognition. The Locobot also uses Candelor, a computer 3d vision library for scene interpretation.

As described in section 4.3, the use of human robot collaboration can only bring benefit if the workplace is taken into consideration of the robot design. By using 3d interpretation software products like Candelor, various production fixtures, components and tools can be used in a random, flexible way. The Locobot program is co-funded by the European Union and in its consortium are international car manufacturers like Audi. It merely underlines the push of industry to develop the fourth segment of human-robot collaboration and increase this form of robotics and its acceptance in the current industrial workplace.

- Safety issues regarding human-robot collaboration;

With the use of industrial robots in the fourth segment of the automation matrix, so called human-robot collaboration, the regulations on safety as were valid before in the other 3 segments are no longer applicable. New rule sets are necessary in both Europe, where the ISO10218 safety standard rules regarding industrial robot arms and their integration, as well as in the United States, where ANSI/RIA standard R15.06-1999 is applied. For practical reasons it has been decided that the ANSI RIA R15.06–1999 can be used until the end of 2014. During the transition, there is a choice of using either the old 1999 R15.06 (R2009) or the new 2012 R15.06. The overlap with the 1999 (R2009) R15.06 allows for a transition for on-going projects and for users to become comfortable with a new standard after 13 years with 1999 R15.06. A specific subset dealing with collaborative robots will be published to handle user requirements. It will provide a collaborative robots / collaborative application guidance, being Part 1, 5.10 & Part 2, 5.11 Collaborative Robot, Definition: Part 1, 3.4 & Part 2, 3.2. These new rules outline robot design for direct interaction with a human, within a defined collaborative workspace (3.3). A Collaborative Workspace falls under Definition: Part 1, 3.5 & Part 2, 3.3. The workspace is a safeguarded space where the robot and a human can perform tasks simultaneously during production operation. The complete requirements for working with collaborative robots are still being determined however. It means for the ISO to identify four levels of (increased) collaboration: where a human enters a robot zone and interacts with the unit, applying a manual or hand guidance to the robot, distance and speed monitoring that allows a robot to move when at a certain space distance and speed from the human and lastly power and force limiting when robots and humans physically interact. The latter two will be included in the not yet released ISO Technical Specification 15066.

It needs to be pointed out here that safety for humans collaborating with robots is a dual sided matter. On one side there is the robot arm itself, on the other the system integration in the workplace. The robot arm is equipped with (but not limited to) torque sensors and/or force sensors that determine thresholds for safe use with humans collaborating. Also arms equipped with soft padding and removal of possible pinch points on the mechanical arm come into play here. Again the concept of lightweight is imperative. The less weight the arms possesses, the smaller the likelihood of hazardous collisions resulting in an injury. Focusing on the technical specification, future safety regulation on human robot collaboration needs to prescribe limits for pressures and forces, which cause injury in case of collisions and or pinching. Because in the past robots and humans were not working together, there are no previously established experience levels. So the new to be established values have to be taken from medical research and practical crash tests on volunteers to determine acceptable pain tolerance levels.

The other side is to be found on the application side, the system integration. An intrinsically safe robot can be very unsafe once it handles pointy, edgy and or sharp objects. For example an eye is easily damaged by a metal pointer in a robot gripper, even when operating within the limits of a "safe" force of 30N. It is up to the end user and system integrator to carry out the necessary risk analysis when applying human robot collaboration robotics in the workplace. The inclusion in the upcoming safety ruling must thus include a determined methodology for required risk assessment for the final human robot application and its work environment for both system integrator and end user. Now the concept of global integration becomes more important. Many larger companies are exporting their locally integrated robot cells. These are often designed by small, medium sized, specialized but local robotics integrators. The harmonization of the European and American safety regulations becomes a requirement in the global market place, both for the benefit of system suppliers and end users alike. It will allow robot manufacturers to design a single global safe robot while end users can more easily move production units across required worldwide locations. The interchangeability of technology will benefit all.

- **Market attractiveness for military robots;**

Worth mentioning is a recent and practical example of reconnaissance robots as described in section 1.2.3.1 by a Norwegian company ProxDynamics, a UAV type robot called Black Hornet. It is a "nanocopter", much like the toy helicopters for sale for less than 10 euro in any supermarket, but following military specifications. The robot is an unarmed UAV. It is in use by Britain's Ministry of Defense. The Ministry of Defense equipped British troops in Afghanistan with these nanocopters UAVs in 2012. Infantry units use the robot for situation awareness, close-quarters scouting, bird-eye viewing and automated surveillance. This type of micro UAV provides real-time video feed of hotspots and other point of interest. It can also send back snap pictures for face recognition and human intel. The Black Hornet nanocopter has a rotor diameter of less than five inch and it weighs less than half a kg including camera. So these types of robots are easy to carry around in a backpack. It can develop speeds of 32 feet per minute on missions and has autonomy of some 25 minutes. The micro UAV has a digital data link with a range as far as 3,200 feet line of sight, GPS or visual navigation through video, autopilot with autonomous and directed modes, and can hover and stare, search patterns automatically, or fly preplanned routes. Based on this success, ProxDynamics received in 2013 a $2.5 million grant from the U.S. Army to develop an upgraded UAV version based on the Black Hornet. It could make the step from reconnaissance robot to assault robot a small but scary one. Current research is done to mount an 11-ounce cannon on a small hand-launched UAV to destroy enemy snipers and other hidden targets with a 12-gauge shotgun shell or high-explosive air burst. This type of UAV uses the video stream in real time send to laptop computers operated by special forces or common soldiers on the ground. They provide for an inexpensive solution indeed. The UAV can be expendable while the support is present when it is needed. Close air support is not always available or in time, while a hand held UAV with assault capabilities can be launched in short time. These kamikaze drones can be remote controlled or autonomous. With their electric propulsion they are also difficult to detect. A factor promoting the use of these light UAVs is the cost issue. Where large unmanned UAV are equipped with state of the art sensory technology, a hand-launched micro UAV typically do not carry this smart sensory equipment for target detection and verification. They become expendable.

Essential in this development is the weight of the (micro) UAV. Less weight means a less powerful motor, freeing up capability for increased payload (assault and/or reconnaissance) and a lighter design for mobility purposes. Current designs are manifold; there are single-, double-, and quad rotor nano UAVs, the traditional fixed-wing micro UAVs, and even bird mimicking flapping wings to keep the robot in the air. Fixed-wing UAV certainly provides for range, allowing infantry soldiers to look at remote areas or provide surveillance over a large area. Copters or rotor driven UAV are typically used for reconnaissance of a limited area or structure, in a more restricted range. In the end it is the mission that determines the type of (aerial) vehicle. The trend of using reconnaissance and/or assault UAV is ever present. According to a pentagon release of December 23rd 2013, the US department of Defense plans to spend US$3.7 billion on research and development, procurement and operations and maintenance of their UAV program in 2014, growing to US$4.8 billion in 2015. Further it has forecasted to invest US$21.6 billion over the course of its five-year defense program.

- **Robotics manufacturers can map their R&D investments based on the practical usability of the research results;**

An interesting example can be mentioned here. It concerns the R&D efforts of Canadian based company Robotiq Inc. and the Japanese robot manufacturer Yaskawa Corp. The need for adaptive teaching was highlighted in chapter 4.2.4. Late 2013 Robotiq Inc. launched the kinetic teaching device, integrated on a Yaskawa standard industrial welding robot. They introduced a first intuitive teaching for arc welding applications. The set-up of a normal welding robot requires in-depth knowledge of robot programming and the actual methods are not intuitive, not even for experienced robot programmers. Also, robot programmers are typically not welders. Welding is a metal joining process that also requires specific welding process knowledge. And especially in welding the path accuracy and movement are more important than in other robotic applications like handling. The way the torch moves over and around the to be joined materials is a crucial factor in the final quality of the welding process.

Traditionally a teach pendant is used to move the welding robot around, driven by buttons or a joystick; clearly far from being intuitive. In addition the robot programmer needs to take into account the various robot axis positions due to the presence of jigs and fixtures and the product itself. The newly launched Robotiq adaptive teaching device allows non-robot educated operators, like manual welders, to teach welding trajectories by hand-guiding the arc weld torch through the desired path. The robot is being programmed like if the welder is welding by hand. Torch orientation and weld parameters can be easily adjusted (on the fly) via a graphic user interface on the teach pendant while running the initial trial runs. It will allow manufacturing, in this case metal arc welding, to have shorter set up times, by non-expert operators, hence lower costs. It shortens and simplifies robot-programming time and reduces costs significantly versus using system integrators to program new parts or employ skilled labor. This example underlines the way the robotics industry is moving its R&D directions in the way as laid out in chapter 4.3 While in this example in concerns the unique use of adaptive and intuitive teaching applied to a standard industrial robot, it does show the way the robotics industry progresses around the concepts of human robot collaboration. Lead-thru teaching itself is not new, however the combination of its use in open platforms, using a graphical user interface operated on low cost effective standard industrial robots makes the function attractive again. The Robotiq product development and launch is not a unique case; German technology research institute and pioneer in service robots Fraunhofer IPA and German welding robot manufacturer Reis Robotics are developing a similar sensor controlled welding robot, achieving equivalent functionalities, to be launched middle of 2014. These new features will find their way into mainstream robotics fast, changing the industry from within.

A secondary benefit of the introduction of intuitive and adaptive teaching for standard industrial robots is that it allows for small and medium sized enterprises to adapt to robotic processes more quickly. Typically these companies lack engineering power to adapt to automation, as do bigger companies. As the example of the intuitive teaching device of Robotiq shows, it allows non expert users to program industrial robots that were only operable by educated labor force and or expensive third party system integration. Along the same lines the quick acceptance rate of the Danish robot manufacturer Universal Robots and their adaptive robots in this segment can be explained. Universal Robots has sold most of its robots in the SME segment. Combined with a powerful graphical user interface, Universal Robots made robotics easy allowing for smaller batch sizes to be programmed by normal operators.

- **Technical research institutes should take the lead in providing a new interface language for robots using gestures;**

A 2013 Canadian study on gestures for human robot collaboration has shown interesting results. Exchange of information between robot and humans, which traditionally occurs via teach pendants or even via buttons on a graphical user interface, would not suffice in the future. Observing human – human gesture interaction during assembly is an effective way to determine what should be communicated in case of human – robot collaboration and how commands should be executed. It deals with the many challenges of dynamic robot movement in a real-time framework of gestures. Acoustic signal interchange is often not practical in a noisy industrial environment, hence the focus on gestures. It turns out that to simulate a basic industrial task of acquiring a part, handling a part and doing joint operation on a part can be executed by simple single-handed gestures. The study made clear that many of the gestures are associated with more than one communication term. It is the context of the task at hand that determines the meaning of the gesture. A similar gesture thus can have different meanings in different tasks.

For human robot collaboration to become effective, both human and robot need to recognize and understand gesture commands from each other. While typical gestures like a raised hand for “stop”, or a pointed finger for “this one” are universal and relatively easy to understand by humans and easy to mimic by robots, other gestures are less obvious. Also human use gestures often together with other forms of body language like facial expressions and or a specific posture. While through Kinect camera systems a robot could possibly interpret these signals together with gestures, it is not a given. So the use of gestures remains limited to a basic level. Reversely, robots expressing body language and facial expressions turn out to be difficult as (most) industrial robots do not have faces. The Baxter robot from rethink Robotics does have a screen with simplistic face-like features for basic information exchange. Humanoids of course have a “face”, but these types of robots are typically not used in an industrial environment. An area to be further researched is where collaborative robots can predict future movement based on a specific gesture set. When an operator leans in to grab an object the robot should be able to distinguish between this being a wanted and an unwanted movement.

The European Commission’s Sixth Framework Programme started in 2013 with the still on-going project SAPHARI (Safe and Autonomous Physical Human Aware Robot Interaction) to investigate human centred gestures for robots. In the project participate 5 European universities, 3 technological research centres as well as industry stakeholders like Airbus / EADS and Kuka Robotics. The project too found that 11 basic gestures performed by a human arm - without contextual information - had a recognition rate of more than 80 %. While the same result applies to the anthropomorphic hand-arm-system: 9 gestures have a recognition rate of more than 80 %.

So on a basic level it should be possible to derive a sub set of gestures and meanings, relating to desired actions by human and robot. The setup of principle definitions of a universal form of "gesture lexicon" becomes necessary. From this work the design of new robot models and software algorithms for gesture based human robot collaboration needs to be assured and build up. It is clear that this research is still in its infant stage. Experiences and new publications lead to a more streamlined development approach. It will take some years before these subsets could be part of a uniform safety regulation like ISO10218, Technical Specification 15066 on human robot collaboration. But this is where the development is going and must go, if human robot collaboration can justify its place in the automation matrix. And gestures are just a part of the total, as the complete workplace itself has to be taken into account during robot system design.

- **Further investigation should lead to a common standard to be used by all active and future robot manufacturers in the human-robot cooperation area;**

Today most robotics manufacturers carry their own development platform and operating software. The lack of unification does not bring the industry forward as a whole. It reduces inter-changeability and prevents shared growth within user companies for multi platforms. On the other hand, present day flexible automation systems are closed subsystems, robots in a cage and locked out from other semi-autonomous sub systems. So present robotics can be compared with a multiple island approach, only to be interlinked by PLC and or bus systems. If we look at the smart phone concept however, we see for example software platforms like iOS and Android, both open platforms that allow users and developers to participate and bring forward applications. This concept has lifted the smart phone industry and acceptance as a whole. A similar shift could occur for robotics, in the human robot collaboration segment. Having an open source robotics platform would allow application builders to create software and use the available hardware for it. Established robot manufacturers as well as start-up companies like Rethink and Universal Robots can generate profits on the manufacturing of the mechanical unit, rather than focus on specialized closed application software. The latter is more of an added value for system integrators, applying the available hardware and developing open source application software and gripper technology, combined with adapted workplace and gesture technology. As we have seen in the examples on robot safety and gesture technology, there are no fixed and written down rules, yet. A joint approach could be more than beneficial here. The collaborative segment is based on the multiple and random interaction between the various components like vision systems, sensors, motion planners, adaptive grippers, software libraries and so on. By a joint approach the market will eventually settle on a workable standard for human robot collaboration.

The good news is that a platform like this already exists. The open source platform ROS, Robot Operating System, could just fulfil the basic requirements. Developed in 2007 by a Stanford University project and based on Switchyard, ROS is a flexible operating software framework for writing robot software. It is considered as an on-going joint approach to collect robotics tools, libraries, algorithms and conventions that can create robot tasks across many robotic platforms. The idea behind ROS is that in order to tackle the many difficult stages in robot software development, independent researchers and institutes can benefit from each other's work and build on each other's progress. The contributors benefit from receiving specific technical feedback from other users and can build upon improvements made by others. The contribution itself can have the form of a simple software driver, a supplied library or can even be a full application. This is a typical beneficial feature of all open source software projects. By sharing the source coding it increases the power of ROS, creating its own success, much like the smart phone analogy. Today drivers are available to run most industrial robots on ROS, while Baxter, the Rethink Robotics collaborative 2012 robot project, runs completely under ROS. It allowed Rethink to speed up time to market, not having their resources tied up in the typical robot software issues. Now with many Baxter's in the field and in research centres they also benefit from the feedback. ROS reaches beyond industry; even the popular Mindstorm robots from company Lego run on ROS!

So far the big four robot manufacturers have not embraced ROS and continue to use their own software development program. Also, aside from Kuka, they have not been very active in the development of the collaborative robot segment. It will be a matter of time before they do, and when they do, ROS would make an excellent choice.

- **Strategic information on regions and applications on which further trend analysis can be used for design purposes and research areas;**

The dissertation provides a broad base of information on robotics industry in various regions of the world. Some industrial robot markets are upcoming and fast growing like China, according to 2013 IFR data. This coincides with the upcoming power of China as a military super power. Further research is necessary to the design of the robots, military and industrial alike that will fulfil the needs of the future. Strategic information on regions and the various applications of robotics are essential here. In this respect it is noteworthy to establish that China already started its own production of industrial robots. The Chinese market for industrial robots has increased by an annual average of 41% since 2001. It is now the world's biggest market for industrial robots for the automobile industry. And November 2013 saw the first maiden flight of a Chinese combat UAV. Although information is scare, it is believed that the Chinese UAVs arsenal ranges from small drones to US equivalent models like Reaper or Predator models. The dominance of countries like the United States, Israel and France in UAVs and Japan in industrial robots is a factor that drives countries like China to develop their own technological robot solutions. And not by coincidence the Chinese UAV was used over the disputed islands with Japan in the East China Sea. Robots are the new chess pieces used in present geopolitical power play. Further and deeper analysis on the R&D activities of China with regards to industrial and military robots is needed to support findings and draw comprehensive conclusions.

On the military side since 2012 we have seen a further increased interest, investment and deployment of the various types of military robots. Coalition forces fighting insurgencies instead of traditional warfare, where infantry is suffering from IED attacks, have dramatically shifted and accelerated the development and deployment of certain type of military robots. The previously discussed examples of hand held nano/micro UAV are a good example here. The provided segmentation of the military driver matrix is just a mere starting point for further needed research. More empirical study is necessary to determine the roadmap for future military robotics and modelling. With the face of the type of warfare changing, so does the context of its needed weaponry and the role of robotics therein. A stringent analysis of current warfare and battlefield needs shape the contours of future development. Also, the use of robotics is not limited to the military; law enforcement agencies already have started using these technologies for crowd control, intelligence gathering and antiterrorist operations. So the applications become manifold, while the role of robotics is clear and is here to stay. A further research on these emerging applications on robotics is necessary. And it is not only limited to a technological sense. Experiences from the recent war in Afghanistan have learned that infantry soldiers develop a "part of the team" feeling to their robotics partners. Much like humans relate with pets. While on a rational level a robot is a mere machine, on an emotional level it is much more. Question is how to design a robot that fulfils possible emotional needs, if any? Future design so far has not taken any of these factors into account.

The aging problem as outlined in chapter 2.3.1 is also a factor that needs to be reckoned with. Although not treated in this dissertation, there is the upcoming market for service robots for personal and medical care. The relation between aging workforce and labour availability is for example in the case of Japan will not to be solved with immigration but with robotics. History has shown that improvements in the standard of living are brought forward by technological innovations. Both Germany and Japan show that with robotics and technological advances it allows for higher economic output and productivity, while unemployment remains low.

RECOMMENDATIONS

In the following pages I will highlight personal recommendations on further research, on directions for R&D development and other main interest focused advice related to the dissertation. I will put them in the context of their foundations as described and analysed in the dissertation.

On human – robot collaboration;

The industrial robot industry is on the brink of opening a new segment, the move into human-robot collaboration. For the new design philosophy of these robots to be successful and sustainable, many areas need to be addressed. So far universities and its PhD students, national research institutes and some interested industrial parties have done much of the work. We could consider that tomorrow a robot exists that can cover the functional requirements as laid out in chapter 4, such as having a 2x7 degrees of freedom capability, that poses a sufficient payload, that runs and learns through intuitive teaching, that can operate in an adapted work environment, that is gesture driven and above all that is safe to work with for humans according to the newest safety regulations. So what more do we need?

We would need many professionals to deploy these new robots, work with them and integrate the units into industrial solutions. To make our companies and jobs better and safer the knowledge of these new robots needs to be dispersed. In order to reach a breakthrough and help and stimulate our economies, a broader platform is necessary than just a handful of top universities and national research centres working on these issues. I would recommend for European governments to embrace and adapt this new technology. While many governments speak about the necessity for being competitive and for having a national focus on Research and Development when it comes to robotics investments are still limited. However it would take relatively little investment to realize this for real and have one or more units available in each educational centre. It should be placed in middle level technical colleges and technical universities, in each participating country. In a country like Hungary for example less than 50 units would be needed to cover the necessities of the main technical institutes. While there is not such a robot yet available, a reference could be the Baxter robot by Rethink Robotics, which sells for approximately 25k euro. Hence the total investment, including basic peripherals and necessary offline simulation software runs around 2 million euro. In authors opinion a bargain for a nation like Hungary This amount is scalable to any other European country. It is a minor investment, compared to the possible benefits. It would allow the educational sector to disperse the knowledge around the human robot collaboration in a consistent, coherent and quick matter through its national education programs. Each year Hungarian graduation students on bachelor, master and PhD level would bring the necessary knowledge to the far corners of local industry, making the nation more competitive. Also it brings the education levels on today's technology and needs.

On further market research and analysis – industrial robots;

I strongly recommend a further and thorough market research of the segment where human robot collaboration types are to be applied; industrial assembly lines throughout the geographic and industry type business segments. This research is the basis for directing R&D investiture, pushing from existing prototypes to real market ready collaborative robots. Here my recommendation needs to include sub-segmenting the fourth quadrant from the automation driver matrix. Human robot collaboration is a wide concept and as we have different types of industrial robots for different types of applications we will have different types of collaborative robots for different types of applications. Hence the recommendation goes out to further segment the market and do research on the following sub-segments; Human Presence, Human Guidance and Human Interaction.

Human Presence represents the market segment of human robot collaboration where a human enters an area in which a collaborative robot is active. The mere presence of a person requires a different form of interaction and increased safety features from the robot's perspective. This segment could represent a large part of the market, as there still is a large separation between human and robot. Current software technology already allows operators in the workspace of standard industrial robots while safety is guaranteed by so called dual chain safety systems. They limit the robot from entering zones where the operator is active, i.e. loading a part in a fixture.

While this already would apply to the criteria of human presence, conceptually speaking it is not equivalent to human presence with collaborative robots. Strict research needs to be performed to distinguish the two clearly and determine their attributes and market advantages.

Human Guidance represents the market segment of human robot collaboration where operator(s) apply a manual guidance or force to the robot. A good example to mention here is the final assembly line in a car factory. Bulky items like cockpits, doors and/or other parts must be placed correctly but swiftly. Here human robot collaboration takes the form where the robot acts as an intelligent assisted lifting / placing device, helping humans with the more tedious tasks and correct insertion while humans use their touch and superior 3d vision process.

Human Interaction is the final segment where complete and free collaboration exists between humans and robots, as described extensively in detail in chapter 4. I recommend market research to be done on the various industrial sectors where high manual labor content like electronic/toy assembly, some areas of food handling, aerospace and others prevail. The market constraints and potentials will be different for different sectors, and so the requirements on future collaborative robot design.

On further market research and analysis – military robots;

Military robots are still in their introduction phase, except for UAV. This entails a further evolution of the various types of existing and new military robots. Even in the UAV (or drone) segment, huge differences are becoming apparent, showing simple forms, costing a few thousand euros, till high tech types costing millions of euro per unit. Each with a different function and capability, but all called UAV. Based on the military driver matrix I recommend for further research to reach a more refined definition of the four identified categories (Reconnaissance Robots, Prevention Robots, Logistics Robots and Assault Robots). Only too often the term robotics is wrongly used when applied in a military conjunction. There is a need for having proper definitions based on the setup of an internationally recognized standardization, like exists for industrial robots. It will allow for comparing and monitoring of the numerous developments in the various segments, benchmarking if you like. A better segmentation definition will allow a military leaders to clearly identify their needs according the roles in their local defense planning and to develop specific plans to reach particular objectives with respect to robotic defense forces. Other aspects like the ethical governance could be then focused on specifically identified (sub) segments. How to handle proliferation of certain military robotics technology within these different (sub) segments could be channeled according to better definitions.

On one common programming language;

As the dissertation is not written from a technical point of view but from economic standpoints author will refrain from entering the technical debate and subsequent recommendations. Still the topic of robot programming languages is an important one, not only from a technical point of view, but also from a critical economical trend design viewpoint. Currently the existing large robot manufacturers like FANUC, KUKA, YASKAWA and ABB all work on different robot controller platforms, preventing their interchangeability. A typical 'protect-my-market' approach, each manufacturer raising barriers for competition to enter and end users to leave. But this strategy brings the market only forward by the power of the individuals, not the sum of powers. Therefore I do recommend the joining of forces by having a common operating system and program language for collaborative robots. A bold step forward would be for the four big manufacturers, and eventually others, to either agree on a new common standard or apply the before mentioned 'ROS' robot operating system as the common standard for their future collaborative robots. The market for industrial robots is still growing, and with the upcoming introduction of collaborative robots, the potential market will be much larger. Given these enormous market possibilities having technological barriers like captive programming languages to avoid the proliferation of new technology will only prolong the market introduction phase and thus slow down the acceptance of collaborative robots. And as we have seen in the smart phone example, so called open platforms can push a market into new areas and speed up market acceptance. From a user acceptance point of view I can recommend the common language to be with the highest degree of graphical user interface possible. Text strings and editors are last century's tools. Cloud operated robotics through graphical and voice commands is the way forward. Wireless by all means. Only then will it allow becoming robotics for the masses. Even non-educated operators would embrace this new form of flexible automation. This formula of robotics could be used even by the smallest size of companies, regardless of their engineering capabilities. Also the basic command and information exchange by gestures should be a standard component of a common (ROS) based operating system for collaborative robots. Also from an educational point of view this makes sense, as only one language needs to be mastered. It would allow for development tools to assist in programming and learning to become universal. The interchangeability of robot production platforms between countries would also become much easier, allowing for companies to be transfer platforms where they are needed without the necessity for large investments in user interfacing.

On new safety norms for human-robot collaboration;

Today robots work in a controlled and closed environment and current ISO 10218 and RIA 15.06 safety rules and norms are applicable as such. Flexible automation where humans and robots work together are becoming more complex; use of dual arm technology, use of mobile robotic platforms and use of gestures will only increase this complexity. Obviously for humans and robots alike it will become much more difficult to know and predict each other's movements. The integration of sensor technology is in my point of view essential herein, and should therefore be an integral part of the new safety rules and norms. After all, only through (new) sensor technology is it possible to monitor in real time the position, direction, speeds and intention of human(s) and trajectories of robot arms. The integration and safeguarding of this sensor technology thus becomes key in the aspect of collision avoidance. Algorithms dealing with robot safety and motion planning should be therefore be common, on the previously discussed common operating system. Given the multiple variables set it will be difficult to draw up such a new all compassing safety norm. There is the danger that by trying to minimize 'risk' the full power of collaborative robotics will not be unleashed. Design should follow function, opting for the use of lightweight robots, padded with soft materials. They bring forward at least injury reduction in case of collision.

Safety reviewed from an abstract point of view implies to determine the origin of possible danger and the target of the danger. To guarantee safety while working with collaborative robots the danger needs to be cross-referenced with the degrees and types of potential injuries based on the risk assessment. Safety is derived from the type of response(s) provided by the robot given the existence of an unsafe condition. So in essence it would be my recommendation that the new safety requirements on collaborative robots become contextual and situational adaptive. Where the existing norms are static, based on caged robots, this concept will no longer be valid. And a mere extension of the existing norms to cover all possibilities of the new segment of the automation driver matrix would not suit the collaborative segment. The new safety concepts need to be in line with the requirements of the changing moment. Safety should be applicable for the described segmentation orientation on human presence, human guidance and human interaction, where each category needs a regulation on different (increased) safety norms. Especially human interaction where collisions between human and robot can be intentional and desired requires further research.

On workplace design;

As each house is different, so are each company and its workplaces. Many factors influence the workplace lay-out and design; like task to perform and application, industry type, applied technological culture, applied norms and regulations, product characteristics, geographical location, ambient factors like temperature and presence of hazardous materials and so on. To define one standard for workplace would be an impossible task. Before robots were caged, but now collaborative robots make their inroad into the workplace. If no workplace is alike and we introduce robots that work freely and randomly with humans into the cadre then the variations become endless. So what is needed is a basic understanding of the new workplace design. An understanding taking into account a man-machine interface based on presence, gestures, intent, voice commands etc. While we will not have one standard workplace, we can think of a way that robots see the workplace as a standard. This can be realized, even today, by using 3d cameras to map the static and dynamic components in the workplace. However the starting point is wrong in my point of view. My recommendation on the issue of workplace design and integration of the workplace within robotics is for manufacturers of robot vision systems to broaden their view. Today’s robotic vision is designed – and limited to – the recognition of pattern and shapes of products. While these products can vary in size, shape, form, texture and so on, the robotics vision remains object related. What current robot vision systems don't do is recognize human body parts, nor their movements. Available in the market, and used by technical research centers are Kinect cameras used by game controllers like PlayStation and Wii. These types of cameras register arm, hand, head position and movements, and can to some extend work with intent. For sure these cameras are wonderful for toys – and even applied research – but not very practical in any industrial environment. What is more important, they are not designed from a functional robotics point of view but designed for entertainment. Technically a Kinect can be used with an industrial robot today but there remains a big world of difference and hence the recommendation to develop these sensor technologies from a robotics point of view. I envision these new camera systems for the workplace to be fully controlled from the robot controller, linking functional aspects with the needed safety issues. It would make the adaptation of any workplace functional towards collaborative robotics easy, simple in its set-up and above all safe. Robot vision manufacturers should apply this basic understanding of new vision systems taking into account the realization of business economic thinking in the human-robot segment and action taking in all fields and on all levels of the technology. Only then we can work with a truly integrated system and adapt the workplace freely and safely.

On military robot-ethics;

War and automation alike have been around for centuries. The status of military robots, as laid out in the military robotics driver matrix in chapter 1.2.3, underlines their need and developments. And as history has shown, every once in a while a new technology comes along that is a so-called 'game changer'. This was the case for example with gunpowder and much later the nuclear bomb. This dissertation has shown the lack of public discussion and development surrounding the ethical issues of the degree of autonomy in the deployment of - specifically - assault robots. The use of assault robot technology and applied level of autonomy form an ethical boundary that is just not (thoroughly) discussed. The matter as such has been getting more public attention though lately. The last years have seen numerous incidents where drone attacks killed civilians and innocents, even though these UAV attacks were still man-controlled! It did create a certain degree of public outrage and started an initial debate on the use of drones, both with reference to their legality and their ethics. Noteworthy to mention is the fact that in March 2013 a demonstration was held by Human Rights Watch organization, in the center of London, against so called “killer machines”. According to this stakeholder, machines that can kill without discretion and without human intervention should be internationally forbidden and banned. Killer robots surpass according to them a morale limit. Mrs. Jody Williams, Nobel Peace Prize winner of 1997, is launching an international campaign to outlaw further research on robotic weapons, aiming for "a complete prohibition of robots that have the ability to kill". My recommendation on the matter of military robot ethics is to start to raise the awareness of the issue. What is needed are clear preconditions for a successful and sustainable application of autonomous military assault robots. I strongly recommend actively developing the field of military robot-ethics, for example “Robotics Rules of Engagement”. It should encourage the thinking and development of new rule sets, linking them to existing international law on war like the Geneva Convention, and/or UN Charters like International Human Rights.

A NATO sponsored international military robotics forum could start with taking inventory of the various standpoints. As mentioned before a proper segmentation is needed, as not all assault robots are alike. A UAV operating and attacking cross border has to be seen in a different legal aspect than a mobile infantry robot shooting autonomous at targets at distances of 300m. The outcome of this forum will of course not stop the development of military robotics but it should shape their future design and application. In case of an error and/or malfunctioning of an assault robot, the consequences can be deadly. Therefore I would recommend for military assault robots to always work in a semi-autonomous mode as a maximum tolerable level. A guaranteed “Man in the Loop” approach, where the final decision to engage is always taken by a human, not the machine. Errors and malfunctioning can never be excluded from the equation, but rogue and out of control assault robot are to be avoided at all times. I can further recommend that the translation of the robot ethics should be entered into solid software and hardware controlled safeguards within the robots, programmed to comply with the new rules of engagement.

RELATED PUBLICATIONS

A. Peer reviewed article in journal – Hungarian journal, in foreign language

1. Struijk, Bob "*Robots in Human Society and Industry*", International Journal in Academic and Applied Research in Military Science AARMS, Vol. 10, Issue 1, 2011, pp(183-195), HU ISSN 1588-8789.

2. Struijk, Bob *"Robot Economics Positioning up to the 2008 Crisis",*
   Bolyai Szemle, Vol. 2/2011, pp(167-183), ISSN 1416-1443
   http://portal.zmne.hu/portal/page?_pageid=34,46876&_dad=portal&_schema=PORTAL

3. Struijk, Bob "*Changes in Human Society led by Robots*", Debreceni Műszaki Közlemények 2011/1 pp.(25-34) *(HU ISSN 2060 6869)*
   http://www.mfk.unideb.hu/userdir/dmk/docs/20111/index.html

4. Struijk, Bob "*Robotics in the New Era – Challenges on Robot Design*",
   Debreceni Műszaki Közlemények 2011/3, pp(15-25,) (HU ISSN 2060-6869)
   http://www.mfk.unideb.hu/userdir/dmk/docs/20113/11_3_03.pdf

5. Struijk, Bob "*Robot Production Volume Data Trends and Analysis*",
   Debreceni Műszaki Közlemények 2012/1 pp(1-10) (HU ISSN 2060-6869)
   http://193.6.145.139/userdir/dmk/docs/20121/12_1_01.pdf

6. Struijk, Bob "*Robotics in Human Society – Challenges on Employment*",
   Katonai Logisztika, 2012/2, XX. Évf., pp(81-99), (HU ISSN 1789-6398)
   http://www.honvedelem.hu/containter/files/attachments/33019/kl2012-2_ok.pdf

7. Struijk, Bob "*A new understanding of modern robotics*", HADMERNOK, VII. Volume 2, 2012/6, pp(248-259) (HU ISSN 1788-1919), http://hadmernok.hu/2012_2struijk.php

8. Struijk, Bob "*New Design Philosophy in Military Robotics*", Repüléstudományi Közlemények, , XXIV. évf., szám July 2012. pp(119-135) (HU ISSN 1789-770X)
   http://www.szrfk.hu/rtk/folyoirat/2012_1/Bob_Struijk.pdf

B. Non reviewed journal, abroad, in foreign language

1. Struijk, Bob *"Automation for Spanish car industry",* La Vanguardia, Feb 2007.
   http://publicacionesymedios.net/ADMIN/upload/ind001fanuc4_maq.pdf

2. Struijk, Bob "*Robots and Reliability* " TechniPublications, Auto Revista, No 2.209, pp (82-87), March 2007,
   Purchase via Link:
   http://www.tecnipublicaciones.com/tienda/producto.aspx?idProducto=954

3. Struijk, Bob "*IRS Tokyo",* i-Motion No.10, pp (6-7), Dec 2010, http://www.fanucrobotics.es/~/media/FRIB/Files/Magazines/i-motion%20n10.ashx

4. Struijk, Bob *"Robots – Food for thought",* Next Generation Food, GDS Publishing, April 2010 http://www.nextgenerationfood.com/article/Robots-Food-for-thought/

C. Foreign Language Lecture in International Conference Proceedings

C.1 Peer reviewed

1. Róbert SZABOLCSI – Gerald MIES – Bob STRUIJK – Péter ZENTAY: *FANUC Robotics Project at Miklós Zrínyi National Defense University*, CD-ROM Proceedings of the VIth International Conference „New Challenges in the Field of Military Sciences, ISBN 978-963-87706-4-6, 18-19 November 2009, Budapest, Hungary.

C.2 Non reviewed

1. Struijk, Bob, Lecture on '*Robot Automation*', Auto Parts Makers Conference, Rabat, Morocco, March 2007.

2. Struijk, Bob, Lecture on '*Trends in Automation Technology*' Portorosj, Slovenija, 10-11 Feb 2005; Blok II (http://www.svet-el.si/tita/program.html).

3. Struijk, Bob, Lecture on "*Robotics for the future",* 4th Conference of the Framework Programme: "EU Framework Programmes: From Economic Recovery to Sustainability" . April 13&14, 2010 Valencia, Spain. Reference via Spanish Ministry of Science and Innovation, P6, Session III, *Factory of the Future* http://www.micinn.es/stfls/MICINN/Presidencia%20Europea/Ficheros/Presi_ES_Conferencia_Valencia_Informe_FinalR2S.pdf

4. Struijk, Bob, Lecture on "*Flexible Automation",* Conference "Inspiring Day" organised by technological Research Center *Tecnalia*, Industrial Systems Unit, May 16th 2012, Madrid, Spain. www.inspiring-day.com

PROCESSED LITERATURE

[1.1] McCloskey, Deidre, *"Review of The Cambridge Economic History of Modern Britain"* (edited by Roderick Floud and Paul Johnson), Times Higher Education Supplement, 15 January 2004

[1.2] Szabolcsi, R. ,Mies, G.: *Robotics in Nutshell – Past and Future*, CD-ROM Proceedings of the VI th International Conference "New Challenges in the Field of Military Sciences, ISBN 978-963-87706-4-6, 18–19 November 2009, Budapest, Hungary.

[1.3] International Organization Motor Vehicles Manufacturers, http://oica.net/category/production-statistics/, accessed 22-10-2011

[1.4] "*Origin of the word robot*", the original text is published on http://capek.misto.cz/english/robot.html, accessed 03-10-2010

[1.5] Cotterell, Brian and Kamminga, Johan, "*Mechanics of pre-industrial technology: An introduction to the mechanics of ancient and traditional material culture"*, Cambridge University Press, 1990, ISBN0521428718. OCLC 18520966

[1.6] Noel Sharkey, " *A programmable robot from 60 AD*", New Scientist, July 2007

[1.7] Banu Musa (authors), Donald Routledge Hill (translator),"*The book of ingenious devices (Kitāb al-ḥiyal)"*, Springer, 1979, p. 44, ISBN 9027708339

[1.8] Fowler, Charles B., "*The Museum of Music: A History of Mechanical Instruments*", *Music Educators Journal* (Music Educators Journal, Vol. 54, No. 2) 54 (2): October 1967 , 45–49, doi:10.2307/3391092

[1.9] Marguin, Jean, "*Histoire des instruments et machines à calculer, trois siècles de mécanique pensante 1642-1942"*, Hermann, 1994, p. 48. ISBN 978-2705661663.

[1.10] Chapman, S. D., "*The early factory masters: the transition to the factory system in the midlands textile industry"*, 1967

[1.11] Halacy, Daniel Stephen, "*Charles Babbage, Father of the Computer*" Crowell-Collier Press. (1970). ISBN 0027413705

[1.12] For ISO and Robot standards see http://www.iso.org/iso/home.html, accessed 03-10-2010

[1.13] Westerland, Lars (2000). "*The Extended Arm of Man, A History of the Industrial Robot*." ISBN 91-7736-467-8.

[1.14] IFR, "*World Robotics 2010*", Statistical Department, ISBN 978-3-8163-0599-6

[1.15] US Department of Defense, "*Unmanned Systems Integration Roadmap 2009-2034*", source: http://www.aviationweek.com/media/pdf/UnmannedHorizons/UMSIntegratedRoadmap2009.pdf accessed 11-03-2012

[1.16] Szabolcsi, R. "*Conceptual Design of the Unmanned Aerial Vehicle Systems for the Firefighter Applications",* CD-ROM Proceedings of the 12th International Conference „AFASES 2010", ISBN 978–973–8415–76–8", p4, 27–29 May 2010, Brasov, Romania.

[1.17] Szabolcsi, R. "*Conceptual Design of the Unmanned Aerial Vehicle Systems for the Police Applications*", CD-ROM Proceedings of the 12th International Conference „AFASES 2010", ISBN 978–973–8415–76–8, p4, 27–29 May 2010, Brasov, Romania.

[1.18] Bartoli G. et al, "*Leonardo, the wind and the flying sphere*", EACWE 5 Conference proceedings, page 1, Florence, Italy, 19th – 23rd July 2009.

[1.19] Tesla, Nikola, "*My Inventions*", Electrical Experimenter magazine, Feb, June and Oct, 1919, p106-107

[1.20] Jaugitz, Markus, " *Funklenpanzer, A History Of German Army Remote- And Radio-Controlled Armor Units*", Fedorowicz (J.J.), Canada 2001, ISBN: 0921991584

[1.21] Teletank, source: http://en.wikipedia.org/wiki/Teletank , accessed 26-02-2012.

[1.22] K-Max remote controlled helicopter, source: http://hight3ch.com/k-max-unmanned-helicopter/, accessed 26-02-2012.

[1.23] Big Dog, source: http://www.bostondynamics.com/robot_bigdog.html accessed 26-02-2012.

[1.24] Davor Antonić, Željko Ban, Mario Žagar, " *Demining Robots – Requirements and Constraints*", proceedings Mediterranean Conference on Control and Automation, http://med.ee.nd.edu/MED9/Papers/Robotics/Robotics_3/MED01-121.pdf, accessed 11-03-2012

[1.25] UAV deployment and growth, source: http://www.cotsjournalonline.com/articles/view/100867, accessed 22-09-12

[1.26] Heath, S.G.,"*Unmanned systems: A Genuine revolution in military airfares?*", The Royal Air Forces Air Power Review, 6 *(2), 2003, p33-55*

[1.27] Armed Robotics Vehicle, source: http://defense-update.com/products/a/arv.htm accessed 03-03-2012

[1.28] Róbert SZABOLCSI, *"The Developing Military Robotics"*, Proceedings of the 13th International Conference of "Scientific Research and Education in the Air Force", "AFASES 2011", ISSN 2247-3137, pp. (1190-1198), 26–28 May 2011, Brasov, Romania. (http://www.afahc.ro/sesiune/sesiune.html)

[1.29] Róbert SZABOLCSI, *"Extra-Cheap Solutions Applied for Non-Reusable Unmanned Aerial Vehicle Technologies*", CD-ROM Proceedings of the VIIth International Conference „New Challenges in the Field of Military Sciences 2010", ISBN 978–963–87706–6–0, 28-30 September 2010, Budapest, Hungary.

[1.30] UAV by other countries, source: Newsweek http:/www.thedailybeast.com/newsweek/2010/02/25/defending-against-drones.html, accessed 18-03-2012

[2.1] Robert D. Buzzel, "*Competitive Behavior and Product Life cycles*", Proceedings of the 1966 World Congress, American Marketing Association

[2.2] Day, G.,"*The product life cycle: Analysis and applications issues*", Journal of Marketing, vol 45, autumn 1981, pp 60–67.

[2.3] IFR, "*World Robotics 2010*", Statistical Department,, p.15, ISBN 978-3-8163-0599-6

[2.4] International Federation Robots, Gudrun Litzenberger, IFR General Secretary, press release 07/04/2011

[2.5] Major General James O. Barclay III, "*Eyes of the US Army - US Army Roadmap for UAS 2010-2035*" , p1.

[2.6] IFR, "*World Robotics 2010*", Statistical Department, Table Europe. APP-2, ISBN 978-3-8163-0599-6

[2.7] IFR, "*World Robotics 2010*", Statistical Department,, p.15, ISBN 978-3-8163-0599-6

[2.8] IFR, "*World Robotics 2011*", International Federation of Robots, http://www.ifr.org, accessed 22-10-2011

[2.9] IFR, "*World Robotics 2011*", page IX, International Federation of Robots, http://www.ifr.org, accessed 22-10-2011

[2.10] Zentay, P; Zoller, Z.; Meggyes, A.; Arz, G.: "*Robotical Handling of Polyurethane Foams with Needle Grippers*", Periodica Polytechnica Mechanical Engineering, Hungary, HU ISSN 032- 6051, 1999, vol. 43, No. 2, pp. 229-238, L R E. http://www.pp.bme.hu/me/1999_2/pdf/me1999_2_16.pdf

[2.11] Zentay P. , Arz. G.: "*Design and Study of Robot Grippers for Handling Polyurethane Foams",* Gépészet 2008, (G-2008-H-05), Proceedings of the 6th Conference on Mechanical Engineering, Technical University of Budapest, Budapest, 29-30.May 2008.

[2.12] Zentay, P. ,"*The Behavior of Polyurethane Foams during Robotic Handling*" , PhD Dissertation, Technical University of Budapest, Budapest, 2006.

[2.13] '*Application of Automation in UK Manufacturing*', 27 Sept. 2010, www.eama.info, accessed 04-09-2011

[2.14] International Standard Industrial Classification - ISIC revision 4:10-33

[2.15] http://news.xinhuanet.com/english2010/china/2011-07/30/c_131018764.htm

[2.16] ABB produces robots in China, http://www.abb.es/cawp/seitp202/786ef80518709fdb4825768c00323e07.aspx, accessed 04-09-2011

[2.17] Tianmiao Wang, '*The development of robot technology in China'*, Intelligent Robotics and Applications, Lecture Notes in Computer Science, 2008, Volume 5314/2008, 1-9, DOI: 10.1007/978-3-540-88513-9

[2.18] http://oica.net/category/production-statistics/2008-statistics/ , accessed 04-09-2011

[2.19] René Kemp, Johan Scot & Remco Hoogma, "*Regime shifts to sustainability through processes of niche formation*", Technology Analysis & Strategic Management, Vol. 10, No. 2, 1998, p 175

[2.20] Frost & Sullivan, "*Study Analysing The Current Activities In The Field Of Uav",* ENTR/2007/065, European Commission Enterprise And Industry Directorate-General, Entr/2007/065

[2.21] Hui Pan, Military Aerospace Fiber optics Newsletter, September 2010

[2.22] UAV article, http://212.137.70.163/investintheuk/sectoropportunities/item/102003.html accessed 04-09-2011

[2.23] http://www.helpage.org/resources/ageing-data/global-ageing-statistics/. Accessed 10 Dec 2011

[2.24] Wise, David A. and Gruber, Jonathan, "*Social Security and Retirement Around the World",* Chicago: University of Chicago Press and OECD (2006), *Live Longer, Work Longer*

[2.25] David E. Bloom, David Canning, and Günther Fink , "*The Graying of Global Population and Its Macroeconomic Consequences*", October 2009, Department of Global Health and Population, Harvard School of Public Health,

[2.26] Peter G. Peterson, " *Gray Dawn: How the Coming Age Wave Will Transform America — and the World*" *by* New York: Times Books, a division of Random House

[2.27] Bill Gates, on UN News Centre, http://www.un.org/apps/news/story.asp?NewsID=12287&Cr=robot&Cr1= , accessed 17 December 2011.

[2.28] International Federation of Robots, "*World Robotics 2011*", http://www.ifr.org, chart of *'Annual industrial robot sales per region'* Accessed November 2011

[2.29] R. D. Shelton and P. Foland, "*The Race for World Leadership of Science and Technology: Status and Forecasts",* shelton@ScienceUS.org , 12th International Conference on Scientometrics and Informetrics, Rio de Janeiro, July, 2009, and published in full in the conference proceedings.

[2.30] Hyun Keun Park, Hyun Seok Hong, Han Jo Kwon, and Myung Jin Chung , "*A Nursing Robot System for The Elderly and The Disabled*" , Portland State University, http://www.ee.pdx.edu/, accessed 17 December 2011.

[2.31] Arjen Rensma, "*Healthcare: The Road To Robotic Helpers"*, ScienceDaily*,* August, 2009, http://www.sciencedaily.com/releases/2009/08/090807091200.htm, accessed 17 December 2011.

[2.32] Antonio López Peláez, "*Prospectiva, robótica avanzada y salud Laboral*", published nr 6-2000, p14 to 21. Website of INSHT, Department of Sociología III: Tendencias Sociales Facultad de Ciencias Políticas y Sociología. UNED.

[2.33] Bob Struijk, "*Robotics in the new Era, Challenges on Robot Design*", Debreceni Műszaki Közlemények, March 2011, pp 15-25, (HU ISSN 2060-6869)

[2.34] Minsoo Kang, "*Sublime Dreams of Living Machines: The Automaton in the European Imagination*", February 2011, Harvard University Press, ISBN: 978 0674049352

[2.35] Michael Wood, "*In Search of the Trojan War*", 1985 London: BBC books.
ISBN 9780563201618.

[2.36] http://www.thinkartificial.org/web/the-fear-of-intelligent-machines-survey-results/ accessed 17-12-2011.

[2.37] Bob Struijk, "*Robots Economic Positioning up to the 2008 crisis*", Bolyai Szemle, Vol. 2/2011, pp (167-183), ISSN 1416-1443
http://portal.zmne.hu/portal/page?_pageid=34,46876&_dad=portal&_schema=PORTAL

[2.38] Mori, Masahiro (K. F. MacDorman & T. Minato, Translation) ,"*The uncanny valley* ", 1970, Energy, 7(4), 33–35

[2.39] Orwell, George, "*Nineteen Eighty-Four",* 1949

[2.40] Isaac Asimov, "*Robot series, I Robot*", 1950, Gnome Press, ISBN 978-0-553-29438-5

[2.41] For ISO and Robot standards, see http://www.iso.org/iso/home.html, accessed 17-12-2011

[2.42] Robin Murphy and David D. Woods, July/August 2009, issue of *IEEE Intelligent Systems,* http://researchnews.osu.edu/archive/roblaw.htm

[2.43] Ray Kurzweil, "*The Singularity is Near"*, Penguin Group 2005, pp. 135-136.

[2.44] Suzuki Maruti Workers' Strike, http://www.newsclick.in/india/maaruti-workers-strike-v-victory accessed December 2010

[2.45] Shinsuke Sakakibara, IFR President, publication of the study "*World Robotics 2011 - Industrial Robots*", http://www.worldrobotics.org/, Accessed 17-12-2011.

[2.46] Andrew Liveris, "*Make it in America, The case for re-inventing America*", January 2011, Publisher: John Wiley & Sons, ISBN-10:0470930225

[2.47] Peter Gorle and Andrew Clive, Metra Martech, "The positive Impact of Industrial Robots on Employment", February 2011, International Federation of Robotics IFR.

[2.48] Martin Ford, "*The lights in the tunnel*", published by CreateSpace (September 22, 2009) ISBN-10: 1448659817

[2.49] Easterly, William, "*The Elusive Quest for Growth: Economists' Adventures and Misadventures in the Tropics*", 2001, Cambridge, Massachusetts: MIT Press. pp. 53–54. ISBN 0-262-55042-3.

[2.50] Alex Tabbarok, "*Productivity and unemployment*", December 2003, Marginal Revolution, http://marginalrevolution.com/marginalrevolution/2003/12/productivity_an.html, accessed 17-12-2011.

[2.51] Maj. General James O. Barclay III, "*Eyes of the US Army - US Army Roadmap for UAS 2010-2035*", p1.

[2.52] Michael Hoffman, "*UAV pilot career field could save $1.5B", March*, 2009, http://www.airforcetimes.com/news/2009/03/airforce_uav_audit_030109/. Accessed 17-12-2011.

[3.1] Estey, EP, "*Robotic prostatectomy: The new standard of care or a marketing success?*", 2009 Canadian Urological Association Journal 3 (6): 488–90.

[3.2] Hagn, U., " *The Aspect of Versatility in the Design of a Lightweight Robot for Surgical Applications*", doctor thesis, University of Hannover, 2011, ISBN 978-3-86853-797-0

[3.3] http://www.flightglobal.com/articles/2007/06/05/214446/airbus-uk-using-automotive-robots-in-wing-manufacture.html, accessed 12-12-2010

[3.4] Charles C. Kemp, Aaron Elsinger and Eduardo Torres-Jara, "*Challenges for robot manipulation in human environments",* IEEE Robotics & Automation Magazine, March 2007.

[3.5] Robert Szabolcsi, Gerald Mies "*Robotics in Nutshell – Past and Future"*, CD-ROM Proceedings of the VIth International Conference "New Challenges in the Field of Military Sciences, ISBN 978-963-87706-4-6, 18–19 November 2009, Budapest, Hungary.

[3.6] Bob Struijk, 2011: "*ROBOTS ECONOMIC POSITIONING UP TO THE 2008 CRISIS*" , Bolyai Szemle, Vol. 2/2011, pp(167-183), HU ISSN1416-1443.

[3.7] Robert D. Buzzel, "*COMPETITIVE BEHAVIOR AND PRODUCT LIFE CYCLES*" Proceedings of the 1966 World Congress, American Marketing Association

[3.8] Andy Spilling, "*The year of the smart phone*", http://ezinearticles.com/?2010 ---The-Year-of-the-Smartphone&id=3173949

[3.9] Bob Struijk, "*Robots in Human Society and Industry*", International Journal in Academic and Applied Research in Military Science AARMS, Vol. 10, issue 1 (2011), pp(183-195) HU

ISSN1588-8789.

[3.10] IFR, World Robotics 2010, Statistical Department, Executive Summary p.IX, ISBN 978-3-8163-0599-6

[3.11] Gerd Hirzinger , Sami Haddadin, Alin Albu-Schaffer and Alessandro De Luca, “*COLLISION DETECTION AND REACTION: A CONTRIBUTION TO SAFE PHYSICAL HUMAN-ROBOT INTERACTION*”, Int. Conf. on Intelligent Robots and Systems (IROS2008), Nice, France, 2008, pp. 3356-3363

[3.12] http://www.thinkartificial.org/web/the-fear-of-intelligent-machines-survey-results/, accessed 12-12-2010

[3.13] Miller, K., "*Modeling of Dynamics and Model-Based Control of DELTA Direct-Drive Parallel Robot,*" Journal of Robotics and Mechatronics, Vol. 17, No. 4, pp. 344-352, 1995

[3.14] DARPA Defense Advanced Research Projects Agency, Department of Defense, “*Fiscal Year (FY) 2011 President's Budget”,* February 2010, , Justification Book Volume 1, Research, Development, Test & Evaluation, Defense-Wide – 0400”

[3.15] Kurzweil, Ray, “*The Singularity is Near*”, Penguin Group, 2005, pp. 135-136

[3.16] Captured UAV by Iran, source: http://en.wikipedia.org/wiki/Iran%E2%80%93U.S._RQ-170_incident , accessed 26-02-2012

[3.17] UAV strikes allies in Pakistan, http://www.geo.tv/GeoDetail.aspx?ID=36579 , accessed 22-10-2011

[3.18] Manning, D. Sharon, ”*The Role of Human Causal Factors in U.S. Army Unmanned Aerial Vehicle Accidents*”, USAARL Report No. 2004-11

[3.19] South African robot accident, source: http://www.wired.com/dangerroom/2007/10/robot-cannon-ki/ accessed 22-10-2011

[3.20] Arkin, Ronald C., “The Case for Ethical Autonomy in Unmanned Systems”, Journal of Military Ethics, Volume 9, Issue 4, 2010, Special Issue: Ethics and Emerging Military Technologies ,DOI: 10.1080/15027570.2010.536402, pages 332-341

[3.12] Sullins, John P, “*Roboethics and Telerobotic Weapons Systems*”, IEEE Conference on Robotics and Automation, Kobe, 12-17 May 2009

[3.22] von Clausewitz, Carl, "*on War*", source: http://www.qotd.org/search/search.html?aid=959&page=3, accessed 18-03-2012

[3.23] Major General James O. Barclay III, "*Eyes of the US Army - US Army Roadmap for UAS 2010-2035*, p1.

[3.24] Wallach, Wendell , "*Robot minds and human ethics: the need for a comprehensive model of moral decision making*" , Ethics Inf Technol (2010) 12:p243–250

[3.25] DARPA Department of Defense, "*FY2011 President's Budget*", February 2010, Book Volume 1, Research, Development, Test & Evaluation, Defense-Wide – 0400, page 236.

[3.26] DARPA Department of Defense, "*FY2011 President's Budget*", February 2010, Book Volume 1, Research, Development, Test & Evaluation, Defense-Wide – 0400, page 125.

[4.1] S. Oberer-Treitz, '*New safety paradigm in Human-Robot Cooperation'*, European Robotics Forum 2012, Odense March 2012.

[4.2] B. Lacevic, '*Safe motion planning and control for robotic manipulators',* Information, Communication and Automation Technologies (ICAT), 2011 XXIII International Symposium on Oct. 2011

[4.3] Frida robot by ABB. Source: http://www.abb.com/cawp/abbzh254/8657f5e05ede6ac5c1257861002c8ed2.aspx, accessed 18-08-2102

[4.4] LWR4+ by Kuka AG. Source: http://www.kuka-robotics.com/hungary/en/products/addons/lwr accessed 18-08-2102

[4.5] NextAge by Kawada Industries Inc. Source: http://global.kawada.jp/mechatronics/nextage.html, accessed 18-08-2102

[4.6] UR-6-85-5-A by Universal Robots. Source: http://www.universal-robots.com accessed 18-08-2102

[4.7] Michael Goodrich and Alan C. Schultz. '*Human-Robot Interaction: A Survey. Foundations and Trends in Human-Computer Interaction',* 1(3):203–275, HCI International 2007.

[4.8] P. Rocco, '*Active Control of Safety: the ROSETTA approach*', European Robotics Forum 2012, Odense March 2012.

[4.9] Stolt A. et al, "*Force Controlled Robotic Assembly without a Force Sensor*", proceedings of the 2012 IEEE International Conference on Robotics and Automation, RiverCentre, Saint Paul, Minnesota, USA, May 14-18, 2012

[4.10] Safety of human-robot collaboration, National institute of Standards and Technology, http://www.nist.gov.el/isd/ps/safhumrobcollsys.cfm, accessed 18-08-2102

[4.11] S Calinon et al '*On learning, representing and generalizing a task in a humanoid robot*'. IEEE Transactions on Systems, Man and Cybernetics, Part B. Special issue on robot learning by observation, demonstration and imitation, pages 286–298, 2007.

[4.12] Dr. Haruki Ueno, '*Face and Gesture Recognition for Human-Robot Interaction'*, National Institute of Informatics, Advances in Multimedia, pages 369–376, 2005.

LIST OF FIGURES

[1] “*Cartesian robot*“, source: FANUC Robotics Magyarország Kft. archives

[2] “*SCARA robot* “, source: FANUC Robotics Magyarország Kft. archives

[3] “*6 axis articulated robot* “, source: FANUC Robotics Magyarország Kft. archives

[4] “*4 axis Delta robot*”, source: Adept Technology, Inc.

[5] “*Nazi tracked mine robot Goliath*”. Source: http://www.historynet.com/goliath-tracked-mine-the-beetle-that-started-the-rov-craze.htm, accessed 20-05-2012

[6a/6b] “*Military Robotics Driver Matrix*”, Source: Bob Struijk 2012

[7] “*Dragon Runner reconnaissance war-bot*”, Source: http://www.military.discovery.com accessed 20-05-2012

[8] “*BigDog*”, Source: http://www.bostondynamics.com/robot_bigdog.html, accessed 20-05-2012

[9] “*Demining robot*”, Source: Cpl Marc-Andre Gaudreault, Imaging Division, Valcartier Garrison http://www.combatcamera.forces.gc.ca, accessed 20-05-2012

[10] “*Predator UAV*”, Source: http://www.fastcompany.com/1695219/cia-predator-drones-facing-ip-lawsuit, accessed 20-05-2012

[11] *“Theoretical Product life Cycle”,* Derek F. Hall Strategic Market Planning, P.60, ISBN 0-13-851049-0 01

[12] “*Industrial robot PLC*”, based on data from IFR, World Robotics 2010, IFR Statistical Department.

[13] “*Concentration Curve Industrial Robots 2008*”, FANUC Robotics Magyarország Kft Statistics

[14] “*Robotics Growth Phases 2005*”, B. Struijk, FANUC Robotics Benelux.

[15] “*Robot density per industrial sector*”, IFR, World Robotics 2010, IFR Statistical Department.

[16] “*Robot density per country 2009*”, IFR, World Robotics 2010, IFR Statistical Department.

[17] “*Total annual supply of industrial robots worldwide*”, source: IFR Statistical Department

[18] “*Worldwide supply of industrial robots by industry*”, source: IFR Statistical Dept.

[19] “*Annual industrial robot sales per region*”, source: IFR and national associations

[20] “*Robot density per country 2010*”, source: IFR Statistical Department

[21] “*Automobile production and robot installations 2008*”, by author. Sources raw data: IFR and International Organization Motor Vehicles Manufacturers

[22] “*Labor force participation rates, 2008, by Region, gender and age group*”, Source: Calculated from International Labor Office, Economically Active Population Estimates and Projections, 5th edition, 2009 revision, and Key Indicators of the Labor Market.

[23] “*Aging population shares 2005 and 2050*”, source: UN 2009

[24] “*Population Aging in China and India*”, source: UN 2009

[25] “*Robot density and aged population share*”, Source: UN 2009, IFR Statistical Department

[26] “*Dental robot Showa Hanako 2*”, by Komuro Inc. Japan, displayed on IRS Show Tokyo, Nov 2011. Source: archive B. Struijk

[27] “*Uncanny Valley*”, by http://oxfordstudent.com/2011/04/07/into-the-uncanny-valley/ accessed December 2011

[28] “*Android by Kokoro Inc. Japan*”, on IRS Show Tokyo, Nov 2009, source: archive B. Struijk

[29] Cartoon, unknown artist, source: www.CartoonStock.com accessed November 2010

[30] ”*US Manufacturing Employment as a share of total Employment*”, by Paul Kedrosky, Source: http://www.businessinsider.com/, accessed December 2011.

[31] “*Unemployment per region*”, source: epp.eurostat.ec.europa.eu , accessed December 2011

[32] “*DLR surgeon robot, MIRO*”, by German Aerospace Center, Institute of Robotics and Mechatronics, Robotic Systems. Source: http://www.dlr.de/rm/en/Portaldata/52/Resources /images/bildgalerie/miro_02.jpg accessed 01-09-2011

[33] “*Theoretical Product life Cycle*”, by Derek F. Hall Strategic Market Planning, P.60, ISBN 0-13-851049-0 01

[34] “*Light Weight Robot (LWR)”* by KUKA Roboter GmbH

[35] “*MOTOMAN 7-axis robot (IA20)”,* source: http://www.motoman.si/ uploads/tx_catalogcasestudy/The_Snake_sneaks_into_production_08.pdf, accessed 04-09-2011

[36] “*Delta robot (M-3iA/6A)* ”, by FANUC Corp. Ltd.

[37] “*Automation Matrix for industrial robots*”. By B. Struijk 2012

[38] “*14 axis FRIDA ABB robot”*, source: archive B. Struijk

[39] “*Light Weight Robots Overview”,* by B. Struijk

[40] “*NextAge Dual Arm Robot”,* by Kawada Industries Inc, source: archive B. Struijk

[41] *“New Man/Robot workplace interface”,* source: archive B. Struijk

[42] “*Annual supply of Industrial Robots”*, source: IFR Statistical department, 23 May 2012

ABBREVIATIONS

ABB	Asea Brown Boveri
AC	Alternate Current
AD	Anno Domini
AGV	Automated Guided Vehicles
ARV	Armed Robotic Vehicles
BC	Before Christ
BRIC	Brazil Russia India China
C2	Command & Control
C3	Command, Control & Communications
C4ISR	Command Control Communications Computers Intelligence Surveillance and Reconnaissance
CCTV	Closed Circuit Television
CE	European Community
CIA	Central Intelligence Agency
CNC	Computer Numerical Control
CPU	Central Processing Unit
DARPA	Defense Advanced Research Project Agency
DC	Direct Current
DoF	Degrees of Freedom
DLR	German Aerospace Center
EU	European Union
G7	Group of Seven: economic alliance of Canada, France, Germany, Great Britain, Italy,

	Japan and the US
GM	General Motors
HERB	Home Exploring Robotic Butler
HR	Human Resource
IFR	International Federation of Robotics
IED	Improvised Explosive Device
IO	Input Output
ISO	International Standard Organization
KIA	Killed in Action
Kg	Kilogram
LIDAR	Laser Imaging Detection and Ranging
m/s	meter per second
NATO	North Atlantic Treaty Organization
NBC	Nuclear Biological Chemical
OEM	Original Equipment Manufacturer
PbD	Programming by Demonstration
PC	Personal Computer
PDA	Personal Digital Assistant
PLC	Product Life Cycle
R4H	Robots for Healthcare
R&D	Research & Development
ROM	Read-only Memory

SME	Small Medium Enterprise
TCP	Tool Center Point
TNO	Netherlands Organization for Applied Scientific Research
UAV	Unmanned Aerial Vehicle
UAS	Unmanned Aircraft Systems
UGS	Unmanned Ground Vehicles
UK	United Kingdom
UMS	Unmanned Maritime Systems
UN	United Nations
UNECE	United Nations Economic Commission for Europe
US	United States of America
USB	Universal Serial Bus
W	Watt
WWII	World War II
ROI	Return on Investment
SCARA	Selective Compliance Assembly Robot Arm

ASPIRANT’S PROFESSIONAL SCIENTIFIC CV

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30 October 1965	born in Amsterdam, The Netherlands (Dutch citizenship)
1972-1977	Elementary school Oosterhout, The Netherlands
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