HADMÉRNÖK

VII. Évfolyam 2. szám - 2012. június

Bob Struijk
struijkb@fanucrobotics.hu

A NEW UNDERSTANDING OF MODERN ROBOTICS

Absztrakt/Abstract

Az ipari robotok egy új korszakba léptek. A robotok gyárainkban átmenetet képeznek egy egyszerű manipulátor, a teljes ipari robot, majd később az intelligens robotok között. Napjainkban a robotok kölcsönhatásba lépnek az emberekkel a munkahelyeken. Ahhoz, hogy megértsük a jelenlegi trendeket, illetve felvázoljuk az ipari robotok adaptív rugalmas automatizálásának fejlesztését, valamint, hogy ezeknek milyen hatásai lesznek a munkahelyekre, vagy magukra a robotokra, számos tényező meg kell vizsgálni.

The use of industrial robots is entering a new era. Robots in our factories made the transition from a simple manipulator to a full industrial robot and later to intelligent robots. Now robots will interact with humans in the workplace. To understand the trends and how current industrial robotics for adaptive flexible automation will develop and what its effects are on the robots themselves and our workplace large number of factors can be investigated.

Kucsszavak/Keywords: *robotika, ember-robot kooperáció, robot ~ robotics, human-robot cooperation, robot*

RELATED WORKS

Industrial robots are used industry wide, in a broad range of applications. As they can produce hazard to humans safety is an issue. Oberer in [1] suggests considering three layers of robot safety for specific robot systems. Lacevic in [2] developed rapidly exploring random trees paradigm to establish a collision-free path for robot arms. The basic specifications of the available leight weight robots and prototypes are given in [3][4][5][6]. Trends in Human-Computer Interaction are studied by Michael A. Goodrich and Alan C. Schultz in [7] with respect to 'Human-Robot Interaction'. In [8] P. Rocco reported on the aspects of Active Control Safety, flowing the European Union's ROSETTA initiative.A recent study by Stolt A. et al in [9] reveal Force Controlled Robotic Assembly without a Force Sensor. Special issues on robot learning by observation, demonstration and imitation are investigated by [10] S Calinon et al. In [11] Dr. Haruki Ueno reports on Face and Gesture Recognition for Human-Robot Interaction. As the market is growing the latest data from the Statistical Department of the International federation of Robotics IFR is used in [12].

INTRODUCTION

Opening the compatibility between humans and robots is the final step in manufacturing using robots. The ultimate goal is to have a flexible and dynamic production environment where robots and humans work hand in hand. This paper aims to identify key topics, and challenge problems that are likely to shape the field of robotics in the near future. Till today, the industrial robot has not changed its architecture much over the past decades as it consists of high performance joints powered by servomotors and linked by reducers, converting it into a flexible manipulator. In general, industrial robots harbor a high risk of injury for humans when they are in proximity of a robot. The main dangers 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

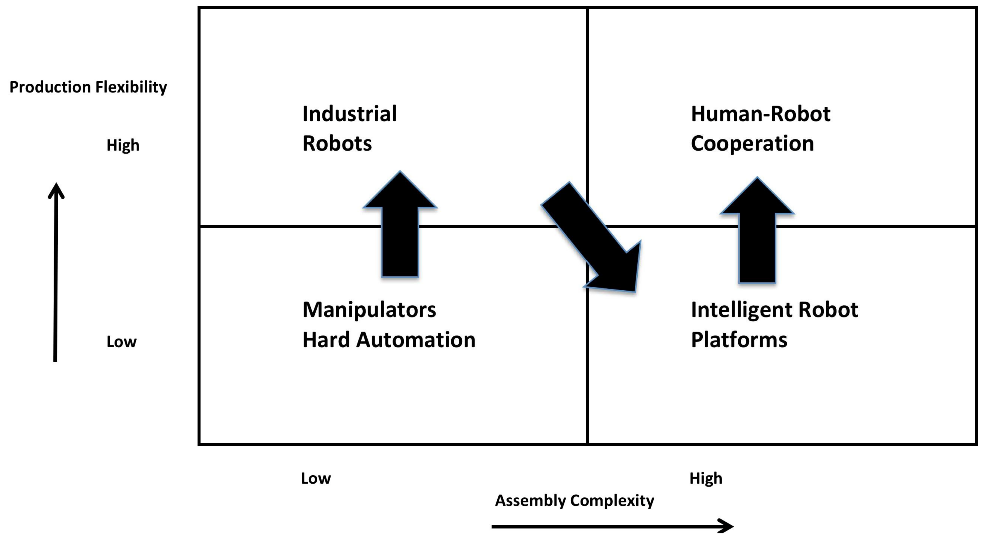
Oberer in [1] suggests considering three layers of robot safety for specific robot systems:

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

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

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

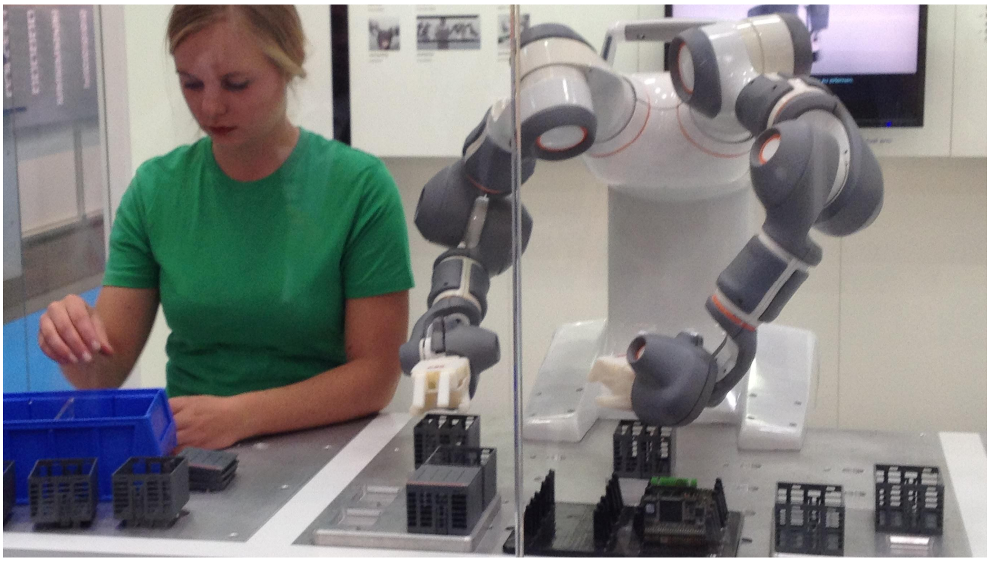
As the current industrial robots are not designed to the above mentioned passive safety criteria, the solution has been so far to remove the human operator away from the robot by placing the latter in an exclusive safety zone. Hard fencing, safety doors, light barriers, pressure mats, security locks and dual chain circuits are all implemented with the goal of keeping the human out of harms way. By keeping the two separated an implicit limitation was set-up with respect to the possible applications and benefits of industrial robots. It was just impossible to automate due to ergonomic constraints of having humans near robots. If we consider as the ultimate objective a fully automated factory, than by analyzing the automation in industry using robots we can identify two scalable main drivers: Production Flexibility and Assembly Complexity. If we combine these two drivers it is possible to group industrial automation on the two identified scales. This Automation Matrix uses the degree of flexibility needed in the production process - if we consider full automation the ultimate goal - and the complexity of the assembly process (With 'assembly' other manufacturing tasks like handling, de-burring, joining etc. are included). Below figure 1 shows the Automation Matrix.



1. figure. Automation Matrix

Traditional automation stared in the first quadrant; where no real level of flexibility is needed and the assembly complexity is low it is enough to use traditional automation equipment, like cylinders, bowl feeders, conveyors, xyz manipulators for handling etc. These machines were in fact the first approach in bringing some form of automation to the production process. In fact this basic form of automation still represents the bulk in most factories. With the birth of the Unimate, the first industrial robot in 1959, the way was opened to reach much higher levels of production flexibility. Today 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 industrial robot operations like spot and arc welding, handling, palletizing, load unload and others provide a high flexibility to factories with large batch series. It supports processes, which are not complex from a robot point of view. Typical complexity is brought forward to the tools attached to the robot or to the machine, which the robot is tending. Starting with the new millennium came the first attempts to use standard industrial robots for complex assembly processes by making the robots 'intelligent'. Hence elevating 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 complexity. Two main elements of intelligence can be named: 2d/3d vision systems and force sensors. The last decade industrial robots are being equipped with these technologies to great success. It allowed the industrial robot to penetrate complex assembly processes, albeit at a low production flexibility level. Embedded vision systems were first used for location positioning and orientation to be able to pick up parts. Later vision systems were used 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 for example. So robots now can see and feel, but are still limited in their use due to the high safety measures needed to protect workers from bodily harm when working with robots. Like animals locked up in a cage. To reach the highest form of flexibility, combining complex assembly systems with high flexibility in the production process, where short batches and high variations are the norm, an adaptive production system is needed for maximum efficiency. This to create the perfect marriage between man and machine: Cooperation between Humans and Robots. An example is given in figure 2. In this quadrant robots and humans literally work hand in hand. Both can now handle sub-assembly, sharing work pieces. Also mobile robots can bring parts to humans for further assembly or inspection. Humans and robots share the same workspace without hindrance of physical safety barriers. In this way both humans and robots can be used in their optimal way. Lacevic

[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 apply their payload, precision and repeatability.



2. figure. Human-Robot Cooperation

To make this possible force sensing in each axis or sensor guided robotic systems are needed combined with low forces and moments.

NEW ROBOT DESIGN

The robots to be used in quadrant 4 of the Automation Matrix of Figure 1 differ conceptually from traditional industrial robots. What is needed are that cause only a low admissible risk or injury at the most. The investigated cases show that its core design is based on the dual arm principle. Analyzing data provided by manufacturers [3] [4] [5] [6] of these new robot models show that the following characteristics for these new industrial robots are required:

- Light weight design
- Dual arm, 14 degrees of freedom (DoF)
- Torque force control actuators
- Easy adaptive teaching
- Low power Consumption

Using these new generation light weight robots allow humans to work side by side or face to face with them, without safety barriers. The robots need to work through Interactive Learning. Because the world is complex, interactions between humans and robots are also complex. According to Goodrich [7] this implies that 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.

Light Weight Design

As stated in the introduction, the main problem with current industrial robots is its multiple sources of hazards. Industrial robots are designed for heavy duty, high cycle. They move at high speed (above 1.5m per second) and move a considerable amount of body mass plus payload. Even a standard mini robot with payload of 5Kg still has a body weight of 32Kg and can move at 2m/s. Current industrial robots are capable of destroying itself, grippers, peripherals and of course harm humans. The use of Light Weight materials such as plastics and aluminum bring down the body mass 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 payload available also is 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 high moments when the robot halts in emergency stop. They can be easily mounted on light structures or mobile platforms to perform different tasks at different locations. Below figure 3 shows the current light weight robots available.

Robot type	# of Arms	Payload	DOF	Weight in Kg	Power Consumption
Universal Robot	1	5Kg	6	18Kg	200W
Kawada NextAge	2	2x1.5Kg	15	28Kg	1500W
ABB Frida	2	2x500gr	14	20Kg	n/a
Kuka LWR4+	1	7Kg	7	16Kg	n/a

3. figure. Light Weight Robots Overview

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. 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, and independent from the tool center point (TCP). A great advantage is when working in narrow spaces, or when obstructions do not allow access with a traditional 6-axis robot. Figure 4 below illustrates an example of a dual arm robot.

4. figure. Dual Arm Concept, NextAge in an aeronautics assembly operation

Robot surface 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 of is the interaction, where robot physically can hand over, in a safe and controlled manner work pieces or tools to humans. It is in fact the next revolution in robotics, where two distinct worlds come together. Summarized benefits of sensor controlled light weight dual arm robots over traditional 6 axes machines 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 [8] the dual arm robots must operate under the Self-Collision avoidance principle when it comes to Safety-oriented path planning.

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 safety circuits. This provided absolute safety but clearly does not allow for human-robot cooperation. So instead of fences, safety doors and light barriers a 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 experimentally verified in a small assembly task. [9]. When the robot touches the human or a fixture a fundamental distinction must be made between a collision 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. Of course this can vary per body part. The robots listed in figure 3 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 of 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.

Easy Adaptive Teaching

Traditional robots are very 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, just to get started) 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 any automobile industrial factory. 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, or programming by demonstration (PbD). 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 [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 lost and we need to consider that adaptive teaching is still in its infant phase, as most robot manufacturers now use their own high level teaching language. Also among the manufacturers there is still no common format agreed.

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 3, can be reduced to a minimum of 200W 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, or even on a guided movable platform. Battery driven operation is possible. Also, due to the low power, collisions are less harmful and make the robot safer. Summarized benefits over traditional 6 axes machines 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.

ADAPTATION OF THE WORKPLACE

With the entry of robots in quadrant number 4 of the Automation Matrix, see figure 1, it is possible to automate using robots the many small and medium sized enterprises (SME) where no high level knowledge base for automation exists. It will require 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 assembly process. To become fully flexible the workplace needs to be reorganized to enable fully the optimization between man and machine. 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 will determine the interaction with the robot. According to Ueno [11] 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 modern 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 5 demonstrates the use of a hand gesture to stop a light weight robot movement based on input by a 3d cognitive vision system.

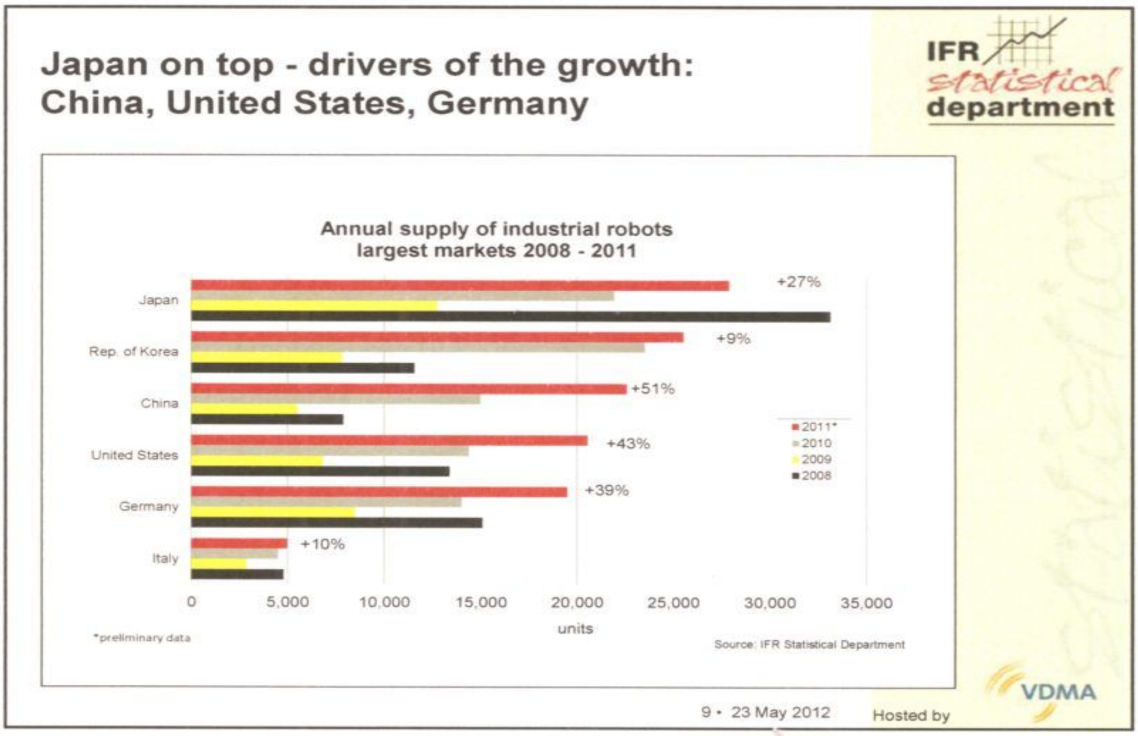
5. figure. New Man/Robot workplace interface

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

ROBOT ECONOMICS

If in the Automation Matrix of Figure 1 we can find most industrial robots in the 2nd quadrant, 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 figures 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 figures. [12] With many countries still exposed to the effects of the before mentioned crisis, this large growth of the use of industrial robots has exceeded by far previous expectations. What is more is that all regions have reported peak levels, see figure 6. Not surprisingly, there have been enormous growth rates reported 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 we 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.



6. figure. Annual supply of Industrial Robots

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 clearly 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. We can clearly 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 main factors remain the key to success for 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 are new sector, in quadrant 4 of the automation matrix where robots work directly with humans So this is a new market segment which comes on top of the existing 165.000 which we now find in mainly 95% in quadrant 2 (industrial robots) and in small degree (5%) in quadrant 3 (intelligent robots). To estimate its market size a further segmentation of quadrant 4 is needed. A definition of what kind of assembly tasks that could typically be carried out by these light weight robots crossed over the various sectors involved. The most obvious sectors are those of electronics assembly (televisions, tablets, mobile phones, toys, computers etc.), fine mechanical parts assembly in metal (pumps, gears, watches, industrial mechanical subcomponents and automotive supply (tier-1 products). These are huge sectors spanning across the globe. Countries like Japan, China, Korea, the US and Germany could benefit highly when these robots enter the market place. A first estimation leads to a unit volume per year of 100.000 year. In Europe this would include the many SME's that now forsake flexible automation due to its high barrier to entry in terms of cost and the typical low planning horizon of these companies.

CONCLUSIONS

Traditional industrial robots have been and are a key factor in flexible automation and this sector is still growing fast. The existing robots work in separated safety zones where human presence is excluded. Current interface between robots and humans is limited. The new generation light weight robots, single or dual arm, are intrinsically safe to work with humans and so open up a complete new market segment. As this segment are new, so are the technology used and the norms regulating it. Using light weight robots enable the robots to be mobile and allow for adaptive teaching, a requirement to enter the huge market of SME's. Light weight robots also require a different human machine interface. The workplace needs to be redesigned where 3d camera systems can track human presence and intent, and where humans can interact with the robots using predefined gestures. The market size where robots interact with humans is sizable and attractive as it is a new segment benefitting from the high acceptance rate of normal industrial robots.

References

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

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

[3] Frida robot by ABB. http://www.abb.com/cawp/abbzh254/8657f5e05ede6ac5c1257861002c8ed2.aspx

[4] LWR4+ by Kuka AG. http://www.kuka-robotics.com/hungary/en/products/addons/lwr

[5] NextAge by Kawada Industries Inc. http://global.kawada.jp/mechatronics/nextage.html

[6] UR-6-85-5-A by Universal Robots. http://www.universal-robots.com

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

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

[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

[10] 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.

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

[12] IFR Statistical Department, press release "Industrial breakthrough with robots", 23 May 2012.

Sources of figures and pictures