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Present and future robot control development—An industrial perspective

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Abstract

Robot control is a key competence for robot manufacturers and a lot of development is made to increase robot performance, reduce robot cost and introduce new functionalities. Examples of development areas that get big attention today are multi robot control, safe control, force control, 3D vision, remote robot supervision and wireless communication. The application benefits from these developments are discussed as well as the technical challenges that the robot manufacturers meet. Model-based control is now a key technology for the control of industrial robots and models and control schemes are continuously refined to meet the requirements on higher performance even when the cost pressure leads to the design of robot mechanics that is more difficult to control. Driving forces for the future development of robots can be found in, for example, new robot applications in the automotive industry, especially for the final assembly, in small and medium size enterprises, in foundries, in food industry and in the processing and assembly of large structures. Some scenarios on future robot control development are proposed. One scenario is that light-weight robot concepts could have an impact on future car manufacturing and on future automation of small and medium size enterprises (SMEs). Such a development could result in modular robots and in control schemes using sensors in the robot arm structure, sensors that could also be used for the implementation of redundant safe control. Introducing highly modular robots will increase the need of robot installation support, making Plug and Play functionality even more important. One possibility to obtain a highly modular robot program could be to use a recently developed new type of parallel kinematic robot structure with large work space in relation to the robot foot print. For further efficient use of robots, the scenario of adaptive robot performance is introduced. This means that the robot control is optimised with respect to the thermal and fatigue load on the robot for the specific program that the robot performs. The main conclusion of the presentation is that industrial robot development is far away from its limits and that a lot of research and development is needed to obtain a more widely use of robot automation in industry.

Keywords: Industrial robots; Robot control; Control functions; Control applications

1. Introduction

The development of industrial robots is characterized by a multidisciplinary fusion of a large spectrum of technologies. Many of these technologies are not specific for robotics and can be developed from solutions in other much larger product areas. However, robot control and then especially robot motion control, is very specific to the robot product and constitutes one of the most important key competences for the development of industrial robotics. By applying and developing advanced control, it is possible to continuously improve the robot performance, which is necessary in order to increase performance and lower cost of industrial robot automation.

It should be emphasized that the automotive industries including their supply chains are the dominating customers for industrial robots of today (UNECE, 2004). This means that the requirements emanating from this type of manufacturing system drive much of the robot development. Thus, most robots of today are well adapted to cost sensitive high volume flexible production in a very competitive environment. This has made it necessary for the robot manufacturers to make very big efforts on the basic requirements on cost efficiency, high reliability and high productivity. Moreover, it has been necessary to adapt the robot control to the plant automation systems with respect to application protocols, communication systems, I/O-interfaces, PLC-equipment, user interfaces, process equipment, etc., for optimal use of the robots and for short change-over times between different products (RIA & NIST, 2000).

In the automotive industry, which will be the starting point for this presentation, full robot automation is usually found for car body assembly, press tending, painting and coating and to some extent for engine and power train assembly (ABB-1, 2003). These applications are well established and the robot

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features with respect to installation, programming, integration, maintenance, performance and functionalities are continuously refined. From a control point of view, this means increasing requirements on robustness, stability and accuracy. At the same time, the cost pressure implies the need of development of less rigid mechanical structures with more complex mechanical robot vibration modes and larger variations of the dynamics of the individual robots, which must be handled by the control system.

Looking further into the automation of car manufacturing, only few robots are used today for the final assembly. Here, new robot technology and new flexible automation solutions are needed to handle the complex assembly tasks and the variability of the product geometries. One big challenge for industrial robotics in the future is to obtain economically feasible solutions to this kind of applications, where robot control needs to deal with tolerances in geometries and processes, to be more intuitive and to be more interactive. A break through in this direction could give a new wave of robotics for a large spectrum of industrial applications, where robots are not realistic to use today. However, before discussing the future of robot control technology, some examples of the ongoing major industrial robot control development will be given. Then the driving forces for the robot development will be discussed and based on this some scenarios about the future will be outlined.

2. Present industrial robot control development

There is a tendency of technology fashion in the development of industrial robots. This usually originates from new production concepts brought forward in the automotive industry. One example of a present popular development is about multi robot control and different solutions are now presented by several robot manufacturers, though a couple of manufacturers already have offered this as a product for some years (Bredin, 2005). The main reason for adopting multi robot control in industry is the possibility to reduce production cost by having robots working in parallel, especially for low speed processes as arc welding. Other benefits are that several robots can be controlled from one controller, floor space is saved, collision avoidance performance can be improved and cycle times can be reduced. In arc welding, it will moreover be possible to obtain a symmetrical heat distribution by welding on the same object from different directions simultaneously. A common set up is to use two or more robots welding on the same work object, which is rotated by a manipulator of one or two degrees of freedom. For higher flexibility, the work object can also be hold by a robot (Fig. 1) and still another robot can hold a component to be welded on the work object. Automotive industry is also interested in reducing the cycle time of spot welding robots by improved coordination of groups of robots working on a common car body. Examples of difficult control tasks, when developing multi robot control for the manufacturing industry, are exact timing of dynamically optimised servo references, smooth transitions between coordinated and not coordinated robot movements, exception handling and failure recovery. When groups of robots work in a large production line

Fig. 1. Multi robot control requires high performance model-based control concepts and efficient methods for robot programming.

there is also the problem of how to dynamically split tasks between robots and between clusters of robots for optimal productivity. Simultaneously, it should be noted that collaborating robots are more difficult to program than single robot installations and therefore off line programming using robot and cell models is even more motivated. One problem then is the accuracy of the collaborating robot installations. Since serially connected kinematic chains have to be controlled, errors in the servo loops and in the models of robot kinematics and dynamics will give bigger pose deviations between the tool and the work object than in single robot installations. Therefore, the development of multi robot control will motivate further improvements of the accuracy of the kinematic and dynamic robot models as well as of the robot servo performance.

Related to the need of multi robot control are the requirements to develop robots with very high load capacity (ABB-2, 2001). Robots handling loads up to 500 kg have been developed to handle, for example, parts of car bodies. Then one heavy load handling robot holds the fixture with the car body components while other robots make, for example, spot- or arc welding. This kind of automation solution is motivated by the higher flexibility obtained when replacing single purpose transport systems with robots. Beside the multi robot control aspect on this, the development towards higher load capabilities result in lower mechanical robot eigenfrequencies, increasing the difficulties to accurately model and control the robot structure.

Another popular development direction is towards new safety arrangements in robot installations (ESALAN Systems, 2006). One short term motivation for this is the possibility to replace electrical and mechanical working range limits with safe software limits, which makes it cheaper and faster to configure a robot cell. Moreover, the safety fences of a robot cell can be more efficiently adapted to the work space limitations, which will save floor space in the workshop. There are also initiatives to develop new concepts for safe direct collaboration between human and robot (Schraft, Meyer, Parlitz, & Helms, 2005). Examples of applications for such collaboration are material handling, machine tending, component transfer and assembly. In order to increase the safety level for human–robot cooperation, the redundancy of the robot supervision of hard- and software is increased, for example, by two channels measurement systems and failsafe bus- and I/O systems. The redundancy needed can of course be obtained in many ways but simultaneously it is important not to increase the cost of the redundancy functionality more than it can be accepted by the applications. One control aspect of new safety concepts is how to make use of the robot models already running in real time in robot controllers to obtain a fault detection that is sensitive enough without giving too many false alarms. It is also important to be able to supervise the safety functionality so it really works when an emergency situation takes place. For example, the brakes and the robot supervision functionality must be cyclic tested. This ongoing development of safety technology could be a first step against the safe robotics needed for future human robot collaboration in less structured environment than in the robot installations of today.

Still another ongoing development direction can be found in using wireless communication in robot systems (Katzel, 2004). The biggest interest for wireless is with respect to the communication between the teach pendant and the controller, but there is also an interest in wireless communication between the robot controller and sensors and process equipment (Frey, Endresen, Kreitz, & Scheibe, 2005). Experiences from test installations have shown that the communication itself is not a major problem in a workshop environment but the big issues are about safety, for example, to find concepts for safe wireless emergency handling and for safe selection of robots at the log in of a teach pendant. It should also be pointed out that since a large spectrum of devices with wireless transmission is produced for the consumer market there are possibilities to make use of such devices as low cost user interfaces to robot controllers (d'Angelo & Corke, 2001). In a robot control development perspective, new safety mechanisms for wireless transmission will be important both with respect to wireless programming devices and wireless sensors and actuators.

A sensor type that has got increasing industrial attention the latest years is the six degrees of freedom (DOF) force/torque sensor (ATI et al., 2006). Even though robot manufacturers have been able to deliver robots with force control (Siciliano & Villani, 2000) for a long time, there has not yet been any wider use of this functionality. Examples of applications where six DOF force/torque sensors are used for the control of industrial robots are grinding, deflashing, deburring, milling, polishing, testing and assembly. In the material removal applications, the advantages with force sensor based control are higher process quality, easier calibration and relaxed requirements on the accuracy of fixtures and grippers (Pires, Ramming, Rauch, & Araújo, 2002) The advantages in assembly are in addition shorter cycle times, reduced impact forces and less risk of jamming, wedging and galling (Zhang, Zhongxue, Brogårdh, Wang, & Isaksson, 2004). In the applications for force sensor based control, manual work with bad working conditions is often found and health risk is therefore also a reason for the introduction of this technology. In order to increase the use of force sensor controlled robots, programming and tuning methods need to be further developed, standard sets of process parameters need to be available and low cost force sensors should be developed. Fast growing applications may be found in the automotive industry and then for drive line component assembly, for example, for shaft insertion, spline matching and torque converter mounting (Fig. 2). Since force- and torque sensing will be necessary in future human–robot collaboration the ongoing force/torque sensor based control development could be important for the understanding of how to integrate this technology into collaborative robotic systems.

Just as for force control, robot vision has been used for a long time without finding any large volume robot applications in the manufacturing industries. One of the reasons for this is the lack of robustness of a 2D vision system in a typical workshop environment and therefore vision systems to control robots are mainly used where the camera scenes are well defined and the light conditions can be controlled, for example, for objects to be picked and placed on conveyors (ABB-3, 2004). However, using the 3D vision products now available on the market it is possible to improve the robustness of robot vision and system solutions can be developed to increase the flexibility in, for example, material handling, machine tending and assembly (Braintech-ref, 2006). Even bin picking can now be made robust enough for industrial use (Watanabe, Kazunori,

Fig. 2. Assembly of automobile drive line components, as the torque converter in the figure, is one example where robot force control has a big potential.

Warashina, & Kumiya, 2005) and there is also the possibility to make use of 3D vision techniques for the calibration of tools, work objects, fixtures and other robot cell components. The main development with respect to 3D vision is of course related to feature extraction and other computer vision problems and the robot control comes in when designing high performance vision interfaces (Lippiello, Siciliano, & Villani, 2005). Related to 3D vision is the laser tracking sensor technology used mainly for the control of arc welding paths when the position of the work object cannot be guaranteed (Servorobot, 2006). These sensor types have been in use for a long time but there is a trend towards full 3D measurements, for example, by the introduction of more than one scanning line in the triangulation-based tracking sensors. The same development trend is also found in optical measurement systems carried by robots for inspection of, for example, car bodies and car sub assemblies. For tracking sensors, it is important to optimise the use and coordination of the look-ahead information in relation to the robot program, to be able to handle situations with lacking measurement data and to be able to perform efficient recoveries from process failures. In a longer perspective, the 3D vision concepts for handling, assembly, tracking, inspection, calibration, etc., can be further integrated into the robot controller and from performance point of view it could then for some applications also be motivated to use 3D vision in the robot servo loop.

Other ongoing improvements of the robot technology are related to the user- and application interfaces of the robot controller with the purpose to make robot programming, operation and maintenance simpler even though the complexity of the robot systems is continuously increasing. Wizard-like step-by-step concepts based on graphical representations of robot movements and process actions are realized also for the use on teach pendants (Fig. 3; ABB-4, 2006), the realistic robot simulation interface is implemented on the robot programming level (RRS, 2006), tools for process modelling are developed to simplify robot programming (Skarin, Claesson, & Bergling, 2004), PLC functionality for logic control and advanced process- and equipment control is integrated into the robot controllers and remote automatic data acquisition of robot production data for optimisation, monitoring, preventive maintenance and fault isolation is further developed. The fault isolation can be based on data from the sensors in the servo loops, special supervision sensors, current and voltage levels in the drive system and virtual sensors using the observer concept. This development will certainly proceed and it is expected that dynamic robot models run in real time will be even more used for fault detection, fault isolation and diagnosis, based on residual generation and system identification methods (Mattone & De Luca, 2003; Ostring, 2002).

Model-based control (Sciavicco & Siciliano, 2000) has been found to be very important in robotics in order to fulfil the contradictory requirements on performance improvements and cost reductions (Fig. 4). The ongoing development is directed towards more complex kinematic- and dynamic models, more complex multiple-input multiple-output (MIMO) control schemes, bigger variations of static and dynamic model parameters, increasing noise- and disturbance levels, larger number of low mechanical eigenfrequencies and enlarged non-linearities. Even if a lot of academic research has been made on all of these aspects, a lot of applied research is needed in order to further improve the model-based robust control of industrial robots. Hand in hand with the further development of model-based control there is an important development of model-based design using virtual prototyping to improve the performance/cost ratio, reduce the development cost and to be able to shorten the product cycles (Pettersson, 2005). Very important is then the mechatronic design approach with development teams consisting of both mechanical design and robot control specialists.

3. Driving forces for the future development of industrial robot control

As for all other industrial products, the main robot development is governed by the need of its users. However, robots are quite unique with respect to its versatility, which means that robot technology is developed towards a large

Fig. 3. Using PC software, touch-screen and efficient tools for application development, the teach-pendant is simultaneously a generic GUI-device and a specialized robot programmer- and operator tool.

Fig. 4. Model-based control of a whole robot family supported by a common controller is obtained by configurable rigid body and elastodynamic models.

spectrum of requirements from different automation concepts and different applications (Robot Manufacturer links, 2006). Starting with the application requirements, development is needed to cope with requirements arising from new processes together with requirements from improvements of traditional processes. New processes are defined here as processes that are new in combination with industrial robots as, for example, friction stir welding, milling, high performance laser cutting, gearbox assembly, flat TV-screen handling and sheet metal deforming. Examples of traditional processes that ask for further improvement of robot performance are water jet cutting, laser cutting, laser welding, gluing, grinding, de-burring, measurement and assembly. Sometimes robot automation gets very popular for manufacturers working with a specific application or material, as an example, the plastics industry is at present very eager to use robotics. Looking at the customer-driven requirements, the base requirements are of course to reduce the production cost and increase the quality of the end products and new automation concepts are tried from time to time to obtain a significant increase in productivity. Examples of such concepts are compact robots, backward bending robots, heavy load robots, multi robot control, accurate robots for off-line programming, flexible framing robots, sensor-controlled robots and safe robots. At the same time, there is the continuous need to improve the flexibility of the use of robots, improve reliability, improve working conditions, decrease life cycle cost, to make installation, system integration, programming and maintenance easier and to increase performance (Fig. 5). All these requirements drive the robot manufacturers to make a continuous incremental

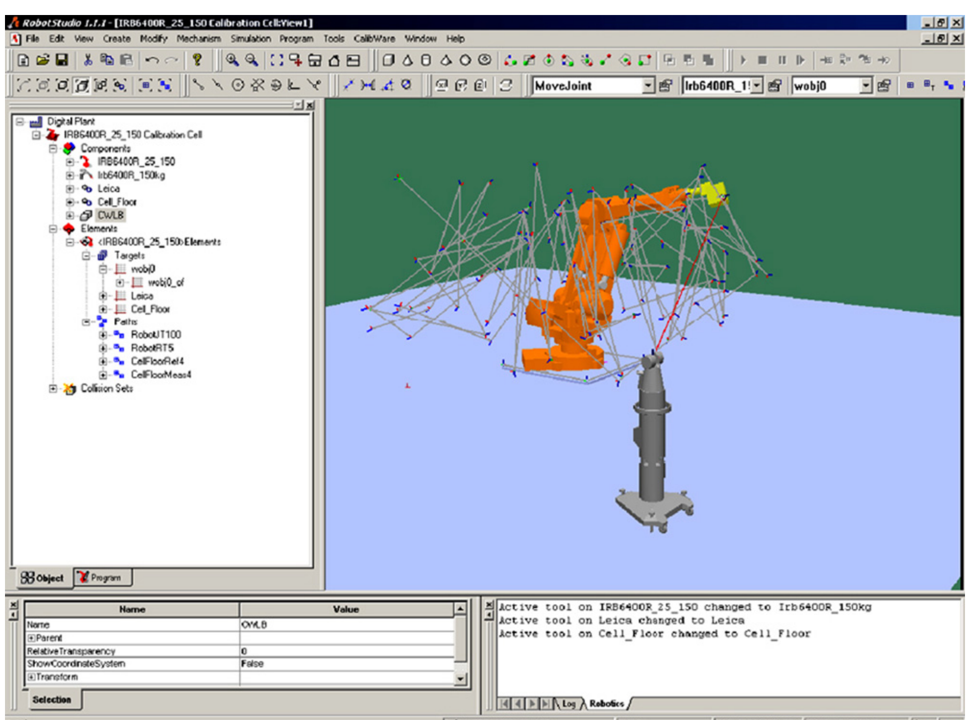

Fig. 5. In order to fulfil the increasing requirements on robot accuracy for off line programming, kinematic and elastostatic identification- and compensation methods are continuously refined and today a volumetric accuracy of ±0.5 mm can be obtained even for a big robot.

development mixed with bigger projects to develop new product generations and new product concepts.

Simultaneously with the customer- and application pull there is of course a technology push that forces the robot manufacturers to take advantage of the latest technology development in other much bigger product segments. Thus, the development of both hardware and software in the PC-area makes a big impact on the robot controller development and efforts are made to use also technology coming from the telecommunication area. The cost of software development and maintenance is continuously increasing and a long software life time is therefore important, which means that, for example, new efficient software development environments and new concepts for scalable system architectures, open interfaces and communication concepts are important drivers of the robot controller development. Even if the fastest development in robotics is found on the controller side, there is also some technology push on the electromechanical side. Examples are more efficient and bigger compact gear boxes, more cost efficient motors and drive systems, cheaper carbon composite material and more advanced tools for mechanical design.

In the long-term perspective, there will for sure be a continued robot development for the automotive industry and its sub suppliers. What could happen here is that increasing fuel prices, pollution and other environmental problems will make it necessary to build smaller and more efficient lightweight cars using, for example, electric drives in combination with fuel cells. Then the question is how this will change the requirements on the manufacturing systems including the industrial robots. One possibility is that spot welding of the car body will be replaced by, for example, laser welding and soldering (Kobe, 2001) for metal parts and riveting, gluing and finishing of composite parts (Brosius, 2006). This could mean a bigger need of smaller and lighter robots with higher precision and rigidity. If electric drives and fuel cells will be commonly used, then new applications will arise, probably with higher requirements on robot accuracy and short cycle times. However, since it is still manufacturing of products in large volumes, probably made by the same industrial organisations that make cars and car components today, the infra structure of the manufacturing system will probably be the same.

As pointed out in Section 1, one part of the car manufacturing that is still labour intensive is the final assembly. Using the robot technology of today for this application, problems arise with the geometric complexity and variability of the work objects, with the space needed for safety fences, with difficult robot programming and with time consuming handling of assembly failures. Only few robot installations can be economically motivated, as, for example, for the gluing and mounting of car windows. In this special case, the health risk is one reason for the introduction of robots. The working conditions are also the incitement for the introduction of equipment to assist at heavy lifts. Here, a development has been running for some years to develop lifting tools from being passive mechanical systems to be powered and servo controlled. These intelligent assistant devices (IAD) are interesting with respect to their safety requirements and the force controlled interaction between the operator and the IAD (Colgate, Peshkin, & Klostermeyer, 2003). However, this kind of device does not give a real automation solution and the concept cannot be developed towards a complete robotized final car assembly. Instead, it could be expected that the automotive industry will push for a new type of assembly robot systems and a new type of infra structure for flexible automation.

In order to find other industries that might drive future robot development, one possibility is to look at manufacturing systems lacking the infrastructure needed for the efficient use of robots today. One opportunity here is the need of automation in small and medium size enterprises (SMErobot, 2005). What is needed in this environment is low cost safe robot systems that are easy to install, configure, calibrate, program and maintain. The application processes will be the same as those that robots are used for today and the biggest challenge will be to develop robot technology that gives a much lower robot life cycle cost. Going further in this development direction there will be a lot of other important areas for the future use of industrial robots. Examples are flexible automation for disassembly (Steele, 2004) and sorting during scrap handling, for cutting up of meat, for other types of food processing and handling (Fig. 6; Hamazawa, 1999), for consumer goods handling, for the assembly and processing of big components for airplanes (KUKA Robotics, 2005), bridges, buildings, ships, trains, trains, power stations, windmills, etc., and for a wide spectrum of craftsmen tasks. If economically feasible solutions for flexible robot automation can be found for these types of applications a huge new market for industrial robots will drive the robot technology development in a new direction.

Looking at driving forces from future new application processes for robotics, enhancement of the robot performance will be very important. It is, for example, well known that arm-type robots are cheaper to manufacture and install than Cartesian manipulators. However, the bandwidth, the stiffness and the accuracy of a Cartesian manipulator can be made much higher than for an articulated robot, but if the performance of articulated industrial robots is significantly increased these robots could take over large market shares from the more expensive Cartesian manipulators. Examples of applications where arm-type industrial robots could then be used are high performance laser cutting, plasma cutting assembly and machining. One example where both improved robot performance and a new flexible automation concept is needed is fettling of iron castings (Lauwers, Wallis, Haigh, & Sohald, 2004). In this case, a third aspect is also important and that is the very unhealthy foundry environment. Having the health problems of the workers in mind, several other future driving applications for industrial robots can be found. Examples of this can be found in slaughterhouses, cold stores, glazier workshops, fisheries and garbage handling plants.

4. Scenarios about future industrial robot control development

Even if it is very difficult to predict the long-term development directions, some scenarios will be outlined to

Fig. 6. The food industry will be one of the drivers for the future robot development. Here, the parallel kinematic robot FlexPicker, based on the Delta concept, works in a bakery.

give an idea about how to make an extrapolation based on the driving forces that can be observed for the use of robotics. Since the automotive industry is the major force driving the robotic development today it could be relevant to start looking at the future of car manufacturing with a scenario based on the earlier proposed need of more accurate, rigid, fast and slender robots for such processes as laser welding, soldering, assembly, riveting and gluing to replace the large number of big heavy robots used for spot welding. Assuming the use of fibre optics and improved Yttrium Aluminium Garnet (YAG) laser technology (Rooks, 2000) and lightweight soldering, riveting and gluing equipment, the weight of the load carried around by the robot will be radically reduced from that of a spot welding gun. This means that it is not far away to look at an implementation scenario for the development of lightweight slender robots with wrist- and upper arm concepts having much lower mass using integrated actuator solutions, fibre composites and other lightweight materials. Even if a lightweight high speed motor together with a lightweight high ratio speed reducer will probably be more expensive than the heavier wrist drive systems used today, the robot installations will probably be cheaper since the main axes can be equipped with actuators having lower power and since less massive frames can be used for the mounting of the robots. In order to make a slender lightweight robot stiff with respect to tool forces, the robot control may need to provide a virtual stiffness, for which sensors are needed in the arm structure of the robot. Examples of sensors are capacitive encoders (Fig. 7) with optional vibration measurement electrodes to measure the angle and the vibrations of the output shafts of speed reducers, joint torque sensors (Pfeffer, Khatib, & Hake, 1989), accelerometers (de Jager, 1994) and strain gauges (Feliu, García, & Somolinos, 2001) to measure arm vibrations. These distributed sensors could then be used by the servo in a sensor fusion manner based on the real time models running in the controller. Important in this scenario will of course be to have accurate dynamic models. An industrial robot is a strongly coupled multivariable system with up to 50 mass-spring elements to be modelled together with the non-linearities originating from friction and lost motion in gears and other transmission components.

A lightweight slender robot concept could also be useful for tasks in the final assembly lines of automobile plants. The scenario in this case must, however, also include the possibility to make intuitive programming and efficient failure handling in direct contact between human and robot, otherwise the

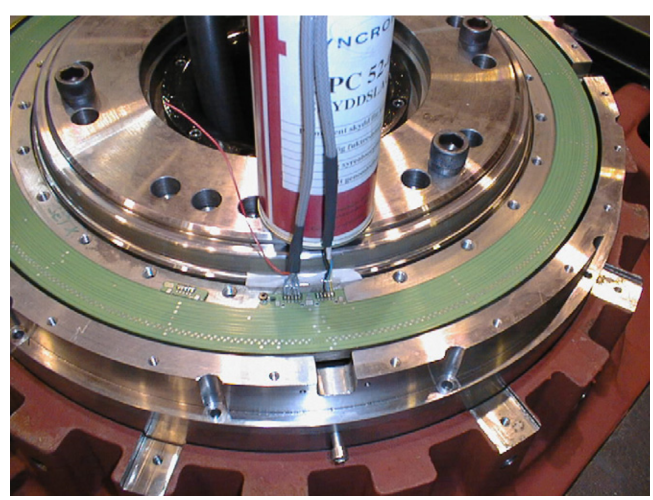

Fig. 7. Capacitive encoder rings (Hexagon Metrology) integrated into an ABB robot joint for accurate measurements of robot arm movements.

automation system will be too complex. Therefore, full safety is needed and a low moving mass and compliant control of the robot is important in this respect (DLR, 2006; Hirzinger, Albu-Schäffer, Hähnle, Schaefer, & Sporer, 2001; Ogawa, Haniya, Okahisa, & Ichibangase, 2005; Zinn, Khatib, Roth, & Salisbury, 2004). In order to obtain a high safety level, it is not far away to make use of the sensors needed for virtual stiffness control also for safety purpose. This could be done by using the redundant measurement signals to generate residuals and to make redundant supervision of the robot control. If also a six DOF force/torque sensor or joint torque sensors are used for human–robot interaction, further redundant supervision can be introduced.

A robot concept for flexible automation of the final assembly of cars could also be used for the assembly of other complex high volume products, to be found, for example, in the home appliance manufacturing industries. It could also be used for the automation of assembly of products with smaller lot sizes and then the concept has some resemblance with the robot assistant concepts found in academic research today (Hägele, Schaaf, & Helms, 2002). However, in order to be able to obtain an economically feasible solution the robots in the mentioned assembly applications cannot work as an assistant to the operator but instead the operator should assist the robots to solve unpredictable problems. The robot installations should then be so robust that one operator could serve several robots. In this respect, it is very important to have a good balance between the autonomy of the robot control and the tasks for the operator. For example, the robot could have some basic failure recovery schemes but infrequent difficult to handle failure situations should be handled by the operator by direct interaction with the robot. An interesting aspect of developing robot control for such human robot collaboration is that the software architecture in industrial robot controllers of today will not be optimal and neither the software architectures for autonomous systems. Thus, new efficient control architectures are needed and the use of a combination of industrial and academic experiences is probably necessary to develop high performance scalable software architectures for these new robot concepts.

A robot that is able to work automatically according to a program generated, supervised, edited and recovered by direct physical interaction between human and robot will of course also solve many of the problems encountered when introducing robots in small and medium size enterprises (SMErobot, 2005). However, these companies usually have much smaller lot sizes than the automotive industry and they represent a much larger spectrum of applications and automation environments than found in the automotive final assembly lines. Moreover, their economy is much more sensitive to big investments and they do not have the access to the automation and robot expertise found in the organisation of an automotive manufacturer. The question then is if it is possible to develop a robot family at the necessary price level for all the small and medium sized enterprises (SME) applications and requirements. One pre requisite for success in this case could be to find a modular robot program, which means that industrial robots will be possible to assemble for different work space sizes, for different load weights and for different performance requirements. The implication of this is that also the model-based robot control must be modular, including modular kinematics and dynamic models. To obtain optimal control for all possible module configurations, automatic servo- and model tuning is needed for each configuration of the robot modules. Since such a highly modular robot concept will increase the difficulties at configuration, re-configuration and maintenance, it will be important to hide the complexity for the user. This means that functionalities must be developed for Plug and Play and intuitive human–robot interaction throughout the lifecycle of the robots. What this could imply is that robot CAD systems need to support robot cell commissioning and design using virtual environment with configuration tools handling Plug and Play components for robot- and cell modules (Gauss, Dai, Zimmermann, Som, & Wörn, 2006). When the selected modules are delivered to the SME site the robot controller should perform automatic cell configuration supported by Plug and Play to make the installation of mechanical, electrical and software modules very simple. At a re-installation of the robot in another application the same configuration tools can be used again, making it easy for an SME to adapt the robot-based production to new products and new customer requirements. In this scenario, new concepts are also needed to be able to support easy to use intuitive robot- and cell calibration and robot programming. One component in such a solution could be the use of multi modal robot–human interaction including lead through (Fig. 8) for the positioning of the robot.

One interesting possibility when building a modular robot family is to use parallel kinematics. Actually, this could be realistic using recently reported parallel kinematic structures with a small footprint in relation to the work space as for serial robots (Fig. 9; Cui, Zhu, Gan, & Brogårdh, 2005; Williams, Hovland, & Brogårdh, 2006). Since the six parallel links in these new structures only need to transmit axial forces and no bending or twisting torques, it is easy to build lightweight robots with very high accuracy and stiffness. These properties are important in, for example, the fettling applications mentioned earlier and since high performance combined with low inertia can easily be obtained also for a large work space, the new structures will be useful, for example, for the processing and assembly of aerospace components and for the processing of other large construction parts as for wind mills, bridges, buildings, railroads, etc., as mentioned before. Moreover, because the mechanical robot structure is not redundant, it is very easy to assemble this type of robots without any requirements on mounting accuracy. This makes these structures ideal for Plug and Play and it could even be realistic to assemble and re-assemble the robots at the customer site without any advanced mounting equipment.

In future robot applications with very complex work objects as in disassembly, sorting, cleaning, cutting up etc. the robots must be supported by advanced vision systems. Probably, 3D combined with colour and texture recordings (Suppa & Hirzinger, 2005) is needed for robust recognition- and measurements on the object structures that will be processed and the vision systems could need assistance from other sensor

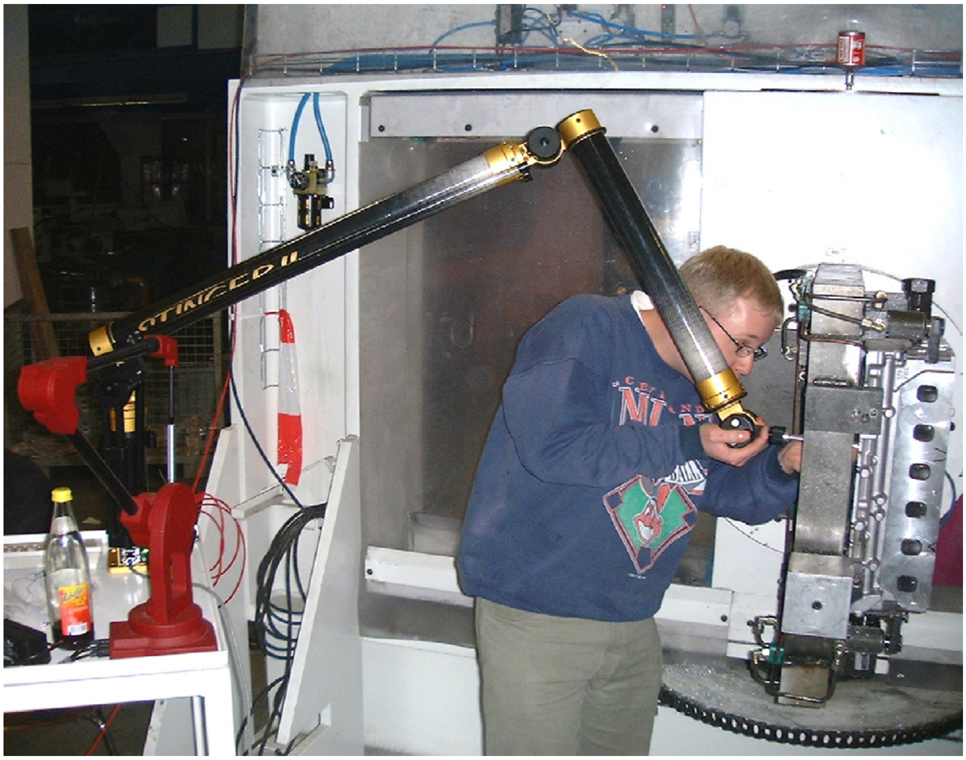

Fig. 8. Lead through programming is expected to be an important technique in order to make robot programming easier. Here lead through programming is performed using a measurement arm connected to the ABB TeachSaver robot programming software.

Fig. 9. A new parallel kinematic robot, developed by ABB, with a work space as a Scara robot but with performance characteristics as a Delta robot.

types to measure not visible characteristics of the work objects. Because of the huge variability in object features and processing rules efficient data bases must be built to model the relations between object characteristics and robot tasks. These process models should be possible to build using the craftsmen's experience. One scenario here is that the teaching is made by the craftsmen themselves by demonstrations on real objects using lead through of the robot while vision systems and other sensors collect object features and the robot controller updates data bases or other repositories with the rules that will be used for the robot task execution. In order to make use of rules and data from other similar installations the robot controllers could be embedded in networks to make use of experience and process models generated on other manufacturing sites. Such system support together with the direct interaction between craftsman and robot could give the possibilities to make future robotics as flexible and easy to use as necessary for the introduction of flexible automation in applications, where manual work force is the only economically realistic solution today.

Beside the more exotic scenarios described above there will of course also be an ongoing development of the robot technology of today. This means further optimisation of the performance/price ratio both with respect to the manufacturing cost of the robots and the life time costs of the robot installations. As discussed earlier robot control is very important in order to get as much performance as possible out of a robot structure. Model-based control using accurate models from system identification of each individual robot will give the future possibilities to push the performance/price ratio further, especially if sensors are introduced in the arm structure of the robot. However, even with the most accurate control the robot performance cannot surpass the fatigue limits of the robot structure and its mechanical components and the torque-, current- and temperature limits of the drive system. Thus, to go further in the optimal use of industrial robots these limits must be tuned to the tasks of the individual robots. One scenario for this is to introduce adaptive robot performance. This means that the controller automatically tunes the drive system parameters to optimise the robot performance for the robot programs that are running. For this thermal and mechanical fatigue models must be executed together with the dynamic robot models in real time to estimate temperature and mechanical stress in critical components and structures. This adaptivity will result in better use of the installed robot and moreover it will make the robot design more efficient since it will not be critically dependent on worst case movements.

5. Conclusions

Industrial robot development has for sure not reached its limits and there is still a lot of work to be done to bridge the gap between academic research and industrial development and to intensify academic research in directions that target new applications and new flexible automation concepts. When developing robot control for real industrial use a lot of unforeseen problems arise and many of these problems need applied research to be solved. It is then very important with a close collaboration between researchers, industrial robot developers, automation system builders and robot users. Some research- and development tasks in the robot control area for such collaboration have been outlined in this presentation and the following is a short summary of the R&D directions that have been discussed:

- Sensor-based robot control for safe interaction between human and robot and simultaneously for high performance control of low cost robot mechanics.
- Sensor-based human–robot interfaces for intuitive robot programming and cell calibration.
- Efficient scalable software architectures for interactive robotics.
- Tools to be used in robot installations for automatic identification and tuning of model-based robot control parameters, especially for highly modular robot mechanics.
- De facto standards and easy to use tools for planning, optimisation, configuring, calibration, programming and re-configuring of robot automation systems. Important concepts could be Plug and Play for both virtual and real components and knowledge databases for process- and automation deployment.
- Further integration of process control into the robot controller, especially in applications where force/torque sensors and 3D vision will be used.
- Extending model-based control with features for adaptive robot performance.

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