Practice for planning and realization of advanced industrial robot systems

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***Abstract*—Conception, planning, realization and installation of industrial robot systems requires the integration of many components that are not designed to work together. In this course many design decisions need to be taken and a significant part of the cost of a robot system is caused by design and integration activities. This holds true particularly for complex or new robot systems as often found in applied research. The main challenges in design and integration of the different components and the state of the art in component integration are presented in this paper. The practice shows that even today where elaborate simulation tools are available practical experiments at early stages of system realization are required. Furthermore, even an economically feasible robot cell might not be economically feasible as a whole if it does not harmonize well with up- and downstream processes.**

***Index Terms*—Robot system, system integration, industrial robot.**

I. INTRODUCTION

While popular literature often cites robots in production or service robot, the sole robot itself is not build to perform a specific task. According to ISO 8373 [1] a robot is defined by the following main characteristics:

- Manipulator with three of more axes
- Programmability and ability to reproduce motion programs
- Universality

Due to the universality a robot cannot perform any specific task out of the box, but requires integration into a robot system (see figure 1).

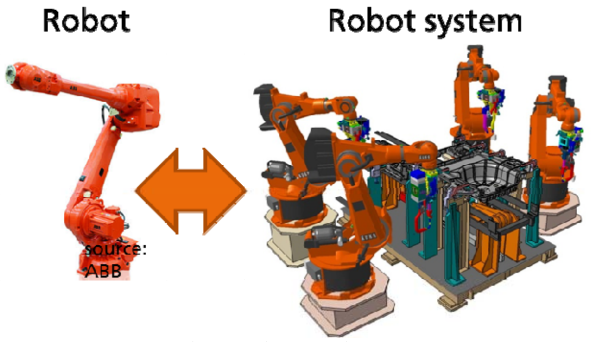

Fig. 1. Robot vs. robot system.

Therefore significant efforts for integration are required to build a robot system out a robot and additional components. An analysis of past automation projects involving robots at Fraunhofer IPA reveal that for a typical industrial robot system the price of the robot system is about 4-5 times of the price of the robot.

II. SURROUNDING CONDITIONS

The unit price of robots when compared to manual labor has dramatically declined in the recent years (see Fig. 2, [1]). At the same time the performance of robots in terms of accuracy, speed, cycle time, load capacity, controller functionality, diagnosis features, and sensor capabilities has dramatically increased. Therefore, today automation using robots is possible in applications that could not be automated in a cost effective way some years ago.

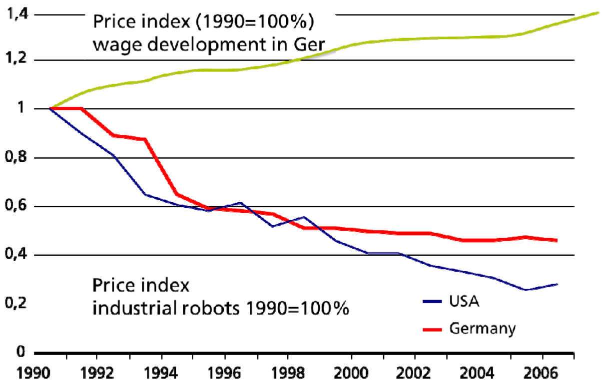

Fig. 2. Price index for robot systems compared to manual labor

So why is automation not yet widespread in particular in small and medium sized enterprises? The three most common reasons for not investing in automation cited by small and medium sized companies are [4]:

- Lot-sizes too small for automation
- Manufacturing processes not suitable for automation
- Automation too expensive

This implies that in particular changeover efforts and reconfiguration of robot systems is too complicated for many companies. As large parts of the cost of the automation system are caused by integration efforts also the cost statement indicates that the integration is too complicated and cannot be managed by these companies. Therefore, one important objective in robotics research should be to facilitate integration, setup, and reconfiguration in order to allow more cost effective production using robot systems at lower quantities or to make automation using robots a viable option for even lower quantities and strongly individualized products.

In the following the specific requirements and current developments for the components and integration of industrial robot systems are outlined.

III. INDUSTRIAL ROBOTS

The robot itself, of course, is the core of the robot system. The classic types of robotic manipulators, namely articulated robots, SCARA robots, and gantry robots have been deeply researched and their properties and application potential is widely understood. These robot types make up approximately 95% of the industrial robot market. Parallel robots have found their application niche in particular for very fast pick and place operations. However, in recent years new types of robots have emerged that will allow building of completely new types of robotic applications broadening the scope of robotic applications. Firstly, cable-driven parallel robots (see Fig. 3, [3]) have been developed from traditional parallel robots. Cable robots allow much larger workspaces than traditional robots, but require, as most parallel robots, much more elaborated procedures during system design.

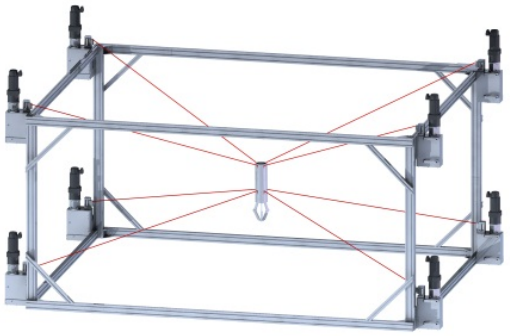

Fig. 3. Cable-driven parallel robot IPAnema

Secondly, light weight robots allow the use of robots in environments where this is currently not possible. While having a classical articulated kinematics, often with an additional seventh degree of freedom, the light structure and the high payload to weight ratio of these robots allows mobile applications that are not feasible with traditional robots. Due to the light structure also direct cooperation with humans become possible. Furthermore, the smaller drives consume less energy and allow power supply through 110 V or 230 V or even low voltage DC power much better suited for mobile application such as production assistants.

IV. END EFFECTORS

The end-effector allows the robot to execute the process and manipulate the environment. End-effectors are typically the most important limiting factor for the flexibility, versatility, and adaptability of a robot system. Handling applications make up about 50% of robot applications in the industry and another 10% of the applications are assembly operations. Therefore, gripping systems are the most important type of end-effector for industrial robots. For selection of appropriate grippers the parameters such as gripping force, gripping jaw displacement, number of fingers, type of finger motion, actuating energy, and the presence of special features, such as measures to keep up the gripping force in case of power loss are most important. Sometimes additional axes are required for accessibility reasons. Further end-effectors are used for welding, coating, assembly, measuring, and machining. Tools are always application specific but should be based on standard components or ideally be composed from a modular building kit that allow the design of application adapted grippers within short time. A new approach in this respect is the 3D-printing of grippers in one part (see Fig. 4). Printing of grippers allows the production of application adapted grippers within short time to relatively low cost. The durability properties are not as good as metal components, but completely suitable for typical SME-type applications, e.g. in loan manufacturing.

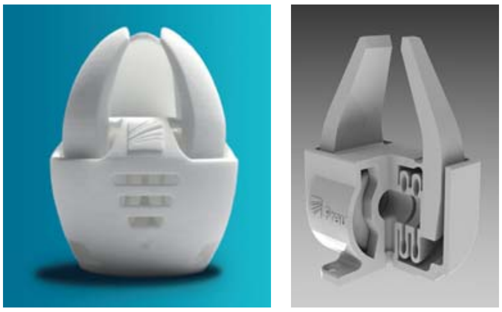

Fig. 4. 3D-printed grippers

V. PROGRAMMING

The programming of industrial robots is traditionally carried out through lead through programming or offline programming. While lead through programming produces a program that can directly be used for the manufacturing task offline programming usually requires program adaptation in the field. For both types of programming an average time requirement of about 60 sec per program point has been found as good estimate in real world scenarios. This value results from an analysis of programs and programming times of automation projects at Fraunhofer IPA. Of course the value depends on the particular set-up of the robot cell, the experience of the worker, and the complexity of the process, but the value can give a rough estimate of the programming time and help to estimate the effort to teach a new product.

Due to this high effort programming times are a major obstacle for the automation of small lot sizes and in high variant production. Alternatives to these types of programming have been under development in recent years and will continue. The first approach is direct interaction of human and robot, e.g. through programming by demonstration (see Fig. 5). Direct interaction allows to implement user interfaces that are much more intuitive than teaching with the teach pendant [5]. Furthermore, physical interaction allows for haptic feedback and therefore enables much faster programming. Through the use of additional sensors approximately programmed points can be transformed to their correct location to speed up programming [6].

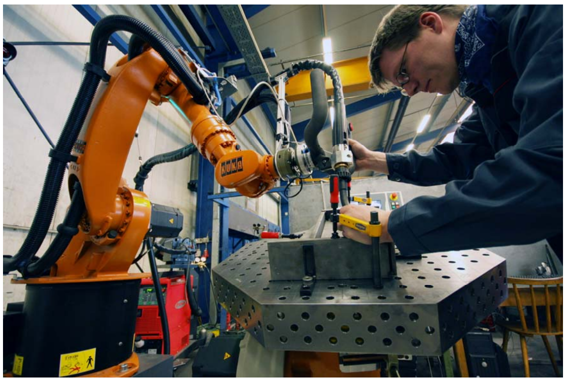
Fig. 5. Programming by demonstration

The second approach under research is fully automatic program generation, similar to CAD/CAM tool chains for machine tools. However, the approaches applied there cannot be transferred to industrial robots due to two reasons:

- Processes for robot systems are much more heterogeneous than for machine tools. They further depend on much more parameters, e.g. material properties, surface properties, etc.
- Uncertainties and deviations play a fundamental role in robotics. For machine tools deviations are avoided through the design of the machine. This is not possible for robots and therefore deviations need to be taken into account.

The implementation of automated programming methods for robots that are not domain specific (e.g. for the application area welding some approaches exist) requires the machine readable formulation of models of the manufacturing technology that can be applied for different use scenarios and application areas and interpreted by the same planning tools.

These approaches are already partly realized in industrial settings and will enable new robotic implementations. In particular allowing re-programming by the end-user by making programming more intuitive will enable more industrial sectors to use automation.

VI. CONTROL SYSTEM

While traditionally the task of the control system of a robot was purely the interpretation of program commands and control of the drives of the robot to ensure coordinated motion, the task have expanded in recent years. Additional sensors require interfaces in the controller that allow for referencing of objects or control of deviations. But the role of the controller will further broaden. Aim of the German initiative Industry 4.0 is the realization of cyber-physical systems, i.e. the combination of mechanics with network connected information capabilities. This will allow new forms of interaction of robot and work piece, e.g. the direct program generation on the robot controller.

VII. DEVELOPMENT PROCESS

As the development of robot systems typically involves many design decisions about a high number of competing system concepts, physical principles, and components that can be used, a structured method to cope with the complexity is required. For example the guideline VDI 2221 [7] of the German Association of Engineers VDI proposes a method for the conception of robot system. The process starts with the precise formulation of requirements. Here it is important also to include requirements of up- and downstream processes and to include solutions to the problem by formulating the requirements in a way that is not neutral to the applied solution. The functions of the system are then split into sub-function to support solution finding. For these sub-functions then solutions are searched by using methods from systems engineering. This is done by finding solutions for single sub-functions and comparing them to the requirements. The solutions are then combined to overall solutions and assessed with respect to the requirements. A solution to be realized is chosen based on this assessment. For the realization of the solution the solution is structured in modules that can be separately designed and tested.

During this process typically questions are raised regarding the feasibility of the developed solutions for the specified task. These questions typically can only be answered through practical testing. During the solution finding process it is important to also observe peripheral problems that are not directly related to the sole technical details of the robot system. Typical trip-wires are:

- Cost for integration of the robot system into the IT infrastructure of the company might make up a significant percentage of the system price and therefore render a sound technical robot cell economically unfeasible.
- Integration into up- and downstream processes is critical in particular for assessing the continuation of production in case of errors of the robot system of upon maintenance.

VIII. SAFETY

Last but not least safety plays a pivotal role in the realization of robot systems. The process for risk reduction as specified in ISO 12100 [8] is outlined in Fig. 6. It always starts from a concrete machine design baseline. As discussed above the sole robot has no specific task. Therefore, in general one can only perform a risk assessment for specific robot cells rather than for robot types. Firstly, the machine boundaries for the machine are identified. This relates to spatial, organizational, life-cycle, and parametric boundaries. Based on this assessment and typical tasks of the robot system the relevant hazards are identified and assessed. If the assessment shows need for improvement of safety risk reduction has to be performed. In this case the process is repeated iteratively until a sufficient risk reduction has been achieved.

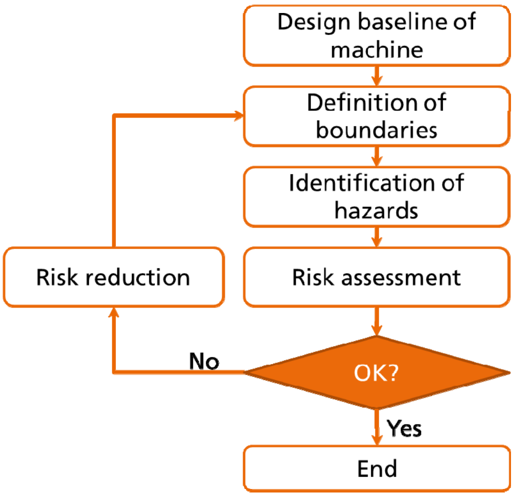

Fig. 6. Process for risk-reduction.

For state of the art robot systems additional aspects have to be taken into account. As specified in the robotic safety standards family ISO 10218 [9], [10] since 2006 human robot interaction is permitted if hazards from the robot are reduced to a sufficient level. These standards currently require that the performance of the robot is restricted in order to ensure safety. Typical measures are the reduction of the robot speed or maximum force that can be applied by the robot. However, these lump-sum safety criteria do not ensure safety in all situations and prohibit many applications that could actually be realized in a safe way. For this purpose research is currently focused on establishing limit values for forces, pressures, and deformation of the human body that are related to biomechanics. The robot system will then be validated against these thresholds by using measurement devices that allow the measurement of these quantities. This shift in the safety assessment will allow new, collaborative robot applications that will allow overcoming limitations that currently inhibit the use of robot systems in some manufacturing scenarios.

IX. CONCLUSIONS

The planning and realization of complex robot systems requires the integration of multiple components that are not engineered to work together. While research in the area of components for robot systems, in particular the robot itself and its control technology is a very active field of research methodic approaches for the handling of complexity in the integration of robot systems receive less attention. The fast pace of innovation in all areas in robotics, in particular in control technology, cognitive features and safety for human machine interaction require constant adaption of the process for integration of robot systems.

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