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# Reconfigurable and Flexible Industrial Robot Systems

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## Abstract

This paper presents a concept for reconfigurable and flexible robot systems. To reach a technology readiness level where solutions and results can be implemented in industry, the focus in this work is on systems with limited number of robots, and work scenarios which are reasonable complex but hard to automate using standard solutions.

Four distinct areas have been identified as important within the concept and further studies: (i) human machine interaction, (ii) safety including collaboration, (iii) programming and deployment, and (iv) planning and scheduling. Feasibility studies have been made which addressed issues (ii) and (iii), in scenarios with collaboration between robot and human, or between two robots. For the chosen work scenario, manufacturing of structures in wood for family houses, challenges related to programming and safety was identified and possible solutions outlined.

The concept and the studies indicate that feasible solutions can be found and designed given a reasonable consistent work processes and products. In this study, the processes are similar, nailing and screwing but different sizes may apply, the material is similar but variations may apply, and the construction is different of each product, but include the same type of operations at different locations. Our study confirm that human collaboration improves the ability to implement and use robots as it make it possible to move some operations to the human which otherwise would add to the complexity of the system. Furthermore, programming can also I general be simplified although methods for automatic programming has been tried out. But in some cases, the solution space is limited and the ability to move certain operations to a human simplifies the programming task. However, further work needs to be done in this area specifically related to safety issues for safe collaboration.

**Keywords:** Human Machine Interaction; Industrial Robot Systems; Reconfigurable and flexible robot systems; Mobile Robots

## Introduction

A general trend in industry is to reduce cost per produced part while at the same time increase the ability to produce on demand. This is related to a situation where the market in the near future can be expected to fluctuate more than today, and technological advances and fierce competition will bring forward new product designs as well as production methods. The result of this will lead to a need for production systems which in an efficient way can meet demands related to frequent product changes and low volumes, which in turn will require robotic systems which are flexible and easy to reconfigure. Research within this area has been on the agenda for decades, and is easy to say but hard to realize. But recent advances in robotics open up new opportunities in developing and implementing methods, design principles and software tools to support the development and operation of highly flexible industrial robot systems [1]. However, flexibility and the ability to adapt or reconfigure a systems is a complex matter and is related to how a system is design, the work processes, how processes can be exchanged or produced in cooperation with other robots or possible human operators.

University West, located in Trollhättan, Sweden, has an R&D focus on production technology and specifically flexible automation and robotics. On-going research at University West includes tools needed to support the operator to reach a high level of reconfiguration and flexibility of robot systems. Research related to reconfiguration and flexible robot systems are often directed towards autonomous or cognitive and intelligent functions. This is of course important but I will here argue for a realistic approach where the operator is considered as an important resource, together with a stepwise development into systems which is able to meet new challenges in production, and possible to implement in industry within a short time horizon.

Robot systems for general use in industry is a complex matter and our approach is to make use of the skill of an operator in the process of resetting a system for a new task. In the discussion in this paper, a boundary condition should be mentioned: A production line where many robot stations or machine tools are integrated into an integrated system is by far more complex than a single robot station, and hence, reconfiguration and flexibility, as well as operator – robot collaborations concerns mainly robot stations with one or a few robots in the discussion in this paper.

Four focus areas which all are important subsystems in robot systems are identified:

Human Machine Interaction (HMI) and collaboration modes,

Safety including collaboration,

Programming and deployment, and

Planning and scheduling.

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By the term collaboration in this context it is primarily meant collaboration between operator and robot system. Through true collaboration, the operator will be an important source through skill and cognitive capability, be an integral part of the robot system, and the robot can act as a co-worker.

## Reconfigurable and flexible robot systems

Reconfiguration and flexibility have been topics on the research agenda for several decades in automation and industrial robotics [2]. Several paradigms have developed over the years, to a large extent based on current technology at the time. It is interesting to compare paradigms and developments in the area of service robots with industrial robots. In general, industrial robots have been,and still is, used as preprogrammed machines with, in most cases limited sensor interaction during task execution. Service robots on the other hand have been developed around the concept or paradigm "sense – plan – act", although it is understood that alternative approaches should be looked for depending on the situation, such as behavior-based or a combination of novel approaches [3]. Although service robots are developed for specific applications and uses, the development in this area can be described as explorative and aiming for a more generic use of robots compared to industrial robots which are dedicated for specific applications and use, prioritizing issues such as robustness, efficiency, repeatability and speed.

However, new developments during recent years have opened up opportunities, which bring the general concept of industrial robots closer to the capabilities and paradigm of service robots. Some key features concern collaboration between operator and robot, and plug and produce concepts which allow for fast resetting and change of the robot system [4]. Although a lot of research is ongoing in this area, industrial uptake is rare and is in most cases limited to demonstrators or pilot installations.

Although robots are characterized by their flexibility, fully automated production units are in general not as flexible as expected. In many cases, today's robot tasks are reasonably simple and consistent, production volume and batch sizes are fairly large, and if these conditions are met, automated systems work excellent under stable production conditions. However, many work operations and processes in industry are difficult to automate using robots. The work processes are relatively complex, production volume low with a need for frequent resetting. In such situations, automation is not always possible by applying traditional robot solutions. Instead, a semiautomatic approach can be applied taking the collaboration between the operator and the robot into consideration, which is made possible in new safety standards for robots and robot systems [5,6].

In the 1990's much research effort were targeted towards making robot systems more flexible and agile manufacturing was developed focusing on large number of product variants and fast resetting of a system [7]. In the late 1990's the Holonic Manufacturing paradigm and concept was developed. It aimed at easy self-configuration, extension and modification of the system [8]. The ability to adapt manufacturing facilities and resources has been addressed by many researchers and only a few can be mentioned here. Reconfigurable manufacturing paradigms and concepts related to flexibility was discussed by [2,7]. Later work addresses the evolvable system paradigm, which includes a few fundamental principles: (i) optimized functionality, (ii) optimized orchestration, (iii) adaptability, and (iv) robustness [9]. This paradigm aims at addressing how to handle and deal with unpredictable scenarios and is able to provide systems solutions over time as conditions changes.

The concept of collaborative robots and/or machines in production has attracted a lot of research but real applications in industrial production using the collaborative concept is mostly implemented as demonstrators or pilot cases. An example on production system oriented research in this area is presented in [10] where the principles and working model for collaborative design and simulation is developed to allow concurrent engineering. An approach based on autonomous production and handling units which can change its task and position on the shop floor is presented in [11]. The framework includes reconfigurable tools for autonomous flexible assembly with integrated sensors, and mobile robotic units which can be transferred around in the shop floor in an efficient way. Moreover, the approach is supported by an intelligent control and monitoring system based on a sensor driven approach and decentralized framework, based on a Service Oriented Architecture. The approach make use of cooperating robots as a main enabler for the reconfiguration to take place. Cooperating robots have the advantage of a possible reduction of fixtures and shortening cycle times during work processes. On the other hand, the complexity increases which involves synchronization of motions, optimization issues, and programming.

The development of robots for professional use (industrial robots and service robots) with the ability to work in a collaborative mode with an operator is likely to evolve into a more general use and mixed applications. See for example [12] where the concept is an autonomous industrial mobile system for general use. The trend is likely to be towards the use of a robot as a "smart tool", which can act as an assistant to humans or other robots, and be capable of working side by side with humans in shared tasks and possibly direct cooperation in tasks [4].

For industrial robots, the safety standards and the collaborative capabilities are developing into systems which can be applied in industry today. Examples can be found at many robot manufacturers like ABB Robotics and KUKA Robot Group which have developed synchronization between robots to perform a common task, such as welding or manipulation and, for operator safety, a dedicated safety controller which monitors and guards the path and motion of the robot manipulator in time and space, see e.g. functions such as "Safe Move" functionality [13,14]. However, the application and actual use of such features for safe collaborative systems is rare and a lot of implementation work is left to the system integrator or user if the full potential of collaboration is to be explored. The standard including related documents for human-robot collaboration is under development (ISO/PDTS 15066 Robots and robotic devices — Collaborative robots) and hence, the application of safe robot systems with human interaction is within reach. To support this, techniques and methods are researched like force-torque monitoring and control for fast detection of collisions of unwanted interaction with an obstacle (or human), see for example [15].

Many components and subsystems which support flexible robotic systems are available or have been developed at companies or in RTD projects. In SME robot (EU IP project), solutions based on intuitive teaching and programming have been developed and demonstrated [4]. The concept was based on a device attached to a 6D force sensors mounted between the robot and the tool which the operator could use to manually drive the robot during programming. Similarly, deployment and programming support were developed that was integrated in a Service Oriented Architecture to support flexible and efficient integration of proprietary software components [16]. Here, deployment was supported by making use of data and information gathered from the World Model (Virtual Factory and Robot Simulation preparation software), and transferring this with the robot task program into an upload process to the robot controller including the teach pendant with specific operator instructions. A concept for a Service Oriented Architecture was developed (based on semantic descriptions and ontology based concept) and demonstrated which included the integration of many sub tasks to actually create, prepare and produce robot programs for a robot, including deployment support. It was found to be a feasible method as many complex problems were found to be easier to integrate and more flexible as different software components from different providers could provide alternative solutions to a specific problem. Of interest here are different methods of communicating and interacting with a system.

Flexible production which includes low volume production and fast change-over requires as discussed above a need for an appropriate HMI, and some work on this was made in the SME robot project. One example was the transfer of instructions based on graphical robot simulation, to the teach pendant, which could be deployment related information, also described in [16]. Such information could include the operator's frequent needs to make on-line calibration and definitions of work objects or other similar tasks, using the teach pendant and robot. A HMI supporting the operator in these tasks would add to productivity and safety. In the FLEXA project where a demonstrator was setup at University West [17], this was taken a step further with a general HMI that included most information and data needed for the operator to manage the production in the station.

Another aspect of low volume production is the need for efficient programming. Tasks may vary in complexity as humans and robots normally work at different pace. Manual tasks requiring "skill" do usually have a relatively long cycle time, and longer cycle time in general adds complexity or at least preparation work for a collaborative task. One attempt to deal with this was made in [18]. The concept developed was a sequence ordering approach to lower the complexity of each task by dividing theses into sub-tasks which, to some extent, could be generated using automatic programming. Depending on the work process and the sub tasks, the preparation and programming are easier to perform using templates or dedicated software components for specific cases. However, our approach is that the actual sequencing of sub tasks in most cases should be managed on-line by the human operator, especially for more complex tasks and low volume down to one-off production.

## A concept for operator supported reconfigurable and flexible industrial robot systems

The objectives of ongoing research at University West within the area of robotics and automation are related to methods, design principles and software tools which will support development and operation of highly reconfigurable and flexible industrial robot systems. The focus is directed towards industrial robots and industrial applications which include support tools for the operator and to some extent autonomous functionality in combination with collaboration between operator and robot system. Applications covers many areas but are in general related to those which involves control and sensing issues, often related to force control or sensors based on optical measurements.

The aim is to support a smooth transition from today's mainly preconfigured and preprogrammed robot systems into adaptable and changeable systems, which can be implemented in a stepwise manner in industry. Four main areas are addressed in this work, all highly industrially relevant in developing and applying robots for flexible automation:

HMI and collaboration modes

Safety including collaboration

Automatic programming and deployment

Planning and scheduling

These areas are all fundamental for developing flexible and easy to reconfigure industrial robot systems for present and future applications. In parallel with researching the four main areas, depicted in red boxes in Figure 1, a demonstrator facility is under development (in blue dashed box) and serve as an experimental platform as well as testing work scenarios. From a methodology perspective, this is also important as it promotes a concurrent and stepwise R&D for each topic as well as the integration of these into the demonstrator facility. The system controller serve on a supervisory level for the robot system and demonstrator.

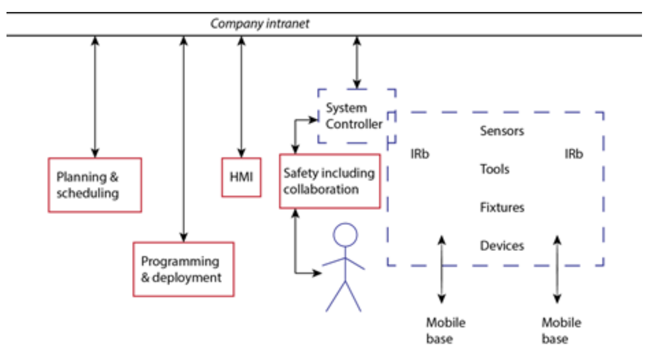


Figure 1: Principal system architecture and parts of the concept and experimental platform. The red boxes are the four main topics and the blue dashed boxes are related to the demonstrator.

An important part of the work relate to collaboration between operator(s) and robot(s). New ways to collaborate between operator and robots will be possible due to new safety standards published and in progress. Many aspects related to collaboration are multi-facetted and need to be investigated, for example, how to perform risk analysis or manage CE-marking,

and safety for reconfigured systems; how to develop and use wireless and handheld HMI devices which can reduce cost of the system and support the operator in operating the system, proper and efficient collaboration modes between operator and robot system, specifically related to reconfiguration, etc.

Reconfiguration and flexibility are to a high degree dependent on how easy it is to adapt/change an automation system to new production scenarios (new products, variants, processes, etc.). Fundamental issues for this relates to programming of tasks. Programming might include various aspects on simulation, such as robot simulation or discrete event simulation, scheduling and planning. For general cases, automatic generation of programs and simulation models is a challenging task, but for product variants with some defined and known similarities we expect it to be feasible to use, either automatic or supportive tools together with an operator.

The demonstrator facility is based on modern industrial robots, along with relevant safety controllers, mobile robots (AGV), sensors, control systems and dedicated software. Related to developing the demonstrator, feasibility studies have been conducted related to issues related to programming and safety, which concerns effective use of robots in small series production and complex tasks where human intervention was found to be needed. A specific case was chosen to illustrate the problem, with a reasonable complexity and at the same time realistic scenario with respect to its industrial relevance for future implementation. The work scenario concerns manufacturing of components or parts for family houses in wood structures consisting of walls or parts connected to walls, windows or roof, etc. The parts are usually flat structures and work processes consist of handling materials, nailing and screwing. In some cases, the process can be done by a single robot, in others there is a need for two cooperating robots or a collaborative approach with a human co-worker, where one is performing the work operation and the other is holding the work piece. An example of the work scenario is shown in Figure 2. Programming cooperating robots is a challenging task which concerns many aspects related to issues such as collision, motion planning and synchronization. However, in this case we have kept the complexity to a reasonable level and the work process itself is mainly to produce nails or screws at specific locations, which can be taken as numerical information from a CAD system from the house manufacturer. However, a challenge here is that despite the customer has more than 30 models to choose from, the customer is allowed to make almost any changes necessary to the design of the house. Thus, from a manufacturing and robot perspective all parts are treated as unique, although many of them are similar.

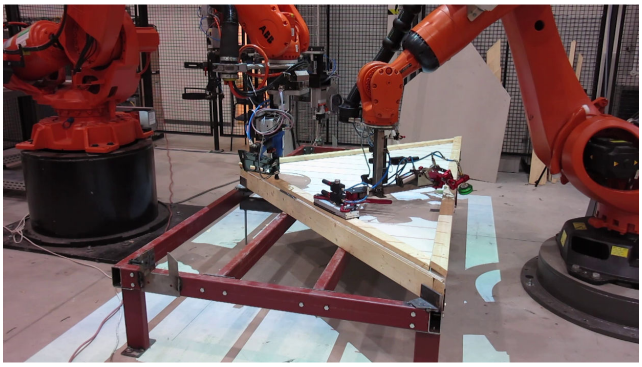

Figure 2: Cooperating robots performing nailing on a wood structure.

From a programming perspective it may be easier to produce programs automatically when the robot is in collaborative mode with a human operator. However, this is of course dependent on the specific situation and this feasibility study is only related to the scenario studied. With the same approach, the human operator can interact by handling and placing material in a proper position and, while holding in position, the robot performs the nailing operation, see Figure 3. In this case, however, the safety is a great concern. Several approaches has been studied including a 3D camera, Pilz SafetyEye [19]. However, it has been found feasible to use different approaches in combinations based on the specific design and need for the work process and robot system, and a combination of camera based techniques which include sectioning using laser scanners, and hand held devices which activate the collaborating robot has been tried out. In addition, the robot controller is equipped with a safe move monitoring function which is able to monitor the motion of the robot during collaborative mode.


Figure 3: Human operator in collaboration with the robot.

## Safety, risk analysis and collaboration

One challenge in a reconfigurable system is to design system safety and related risk assessment to fulfill all relevant requirements described in present and future safety standards. New standards concerning safety requirements for robots and robot systems [5,6], are within the current year (2014) expected to be complemented by a technical report, "Robots and robot devices — Collaborative robots" (draft ISO/PDTS 15066). Furthermore, ongoing work indicates updates of current safety standards in the near future. This will provide an important framework for developing feasible safety systems based on current and future standards, which can be applied as efficient supporting parts for this type of robot stations.

## Programming and deployment

Challenges in robot programming include in general issues such as robot work space and joint limits, collisions, configurations of the robot, accuracy and calibration of workpiece placement and correlation to CAD models, etc. Our approach will be to make use of existing software and, as appropriate, develop added functionality or combine vendor specific software for the purpose of automatic programming or operator support as described in [16].

Once a program is generated and uploaded to the target robot controller, it must be deployed in a way to match the specific configuration of the target system. This includes many practical details on the shop floor such as work object frame definitions, tool definitions and calibrations, I/O definitions, etc., all important parts for reconfigurable and flexible systems. Our approach to these issues are to develop operator supporting tools which will be integrated to the HMI, where simulation support can assist the operator through instructions, graphics and recommended working procedures, primarily based on simulation.

Automatic programming is a challenge for generic applications in industrial environment where it is important to achieve performance and quality with a high degree of certainty. The approach in our work is to develop software tools where programs for the robot are generated automatically but for appropriately sized operations, and let the operator make use of these programs through sequencing, redefining reference frames if needed, etc.

## Conclusion

Reconfigurable and flexible industrial robot systems concerns mainly production where challenges include low production volume of products, frequent resetting of the production system, and complex work operations which in general is difficult to automate. In production, there are many work operations which should be possible to robotize in part, such that an operator (human) takes care of all the skill needed for the overall task, while a robot should work as a smart coworker performing operations which are more suited for a robot than a human. An example could be in wood working where operations like nailing or screwing are typical robot operation, while other operations like precise placement or assembly of wood parts or beams, measurements and quality control, and decisions of in-process changes, are more related to human work. And for products which are close to one-off production, need to be made in a collaborative mode. Another challenge relates to programming. In a collaborative mode and for close to one-off production, programs need to be made automatic, but realistically for small and simple operations, which the operator can put together into sequences. Again, the support of an operator in flexible production is clear, and to make that work, the system must be supported by appropriate safety measures and HMI which contribute to an efficient communication.

The aim of this work is to expand the overall use and application where industrial robots can be applied and provide methods and tools which makes it possible to partially robotize work operations and production which has been manual today. The technology for this is available and a next step in the use of industrial robots is likely to be seen within the next few years.

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