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Exploring a Model for Production System Design to Utilize Large Robots in Human-Robot Collaborative Assembly Cells

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Abstract

It has been shown that large robots can be safely installed for human-robot collaborative assembly cells in experimental setups. It has also been found that these installations require demanding considerations of a significant number of layout and safety parameters. This indicates that successful commercial implementations will require a resource efficient model for production system design that anticipates utilization of large robots in collaborative settings. Experiences from experimental setups have been used to explore a basic model for such production system design, to stimulate a discussion regarding what model characteristics should be tested and validated in future research.

Keywords: Automation, Human-Robot Collaboration; Production Design, Modeling

1. Introduction

Automation of assembly has for a long time been a solution to increase productivity. When evaluating whether automation of assembly can increase productivity, the alternatives have for almost as long time, been to compare

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either manual assembly *or* fully automated assembly. However, advancements within several fields such as programming, robot sensor and control technology, force sensing, environment recognition, human–machine interfaces and safety system technology have made it increasingly irrelevant to have an *either-or* approach when evaluating automation options. These technology developments have made it possible for humans and robots to safely work in absolute proximity, hence increasing the possibilities to take full advantage of the combined strengths of humans and robots, possibly unleashing further productivity potentials. Installations of assembly cells where humans and robots work in absolute proximity are often called collaborative robot installations or cobots, and collaborative assembly cells including smaller robots, where collaboration means "sharing workspace", have been successfully deployed for some years. Collaborative assembly cells including larger robots are, however, still not commonly found or described in academic literature, even though they potentially add further benefits compared to smaller robots, as they can offer a solution for e.g. heavy object lifting without the need to utilize lifting tools, or a solution that overcomes human range limitations. If cobot installations with larger robots are used, there are many alternative methods to handle layout and safety considerations and a model for cobot system design must have the capacity to propose, evaluate and choose effective combinations of different solutions. However, if cobots including smaller robots are introduced in an existing production flow, to handle small components, these installations offer a much smaller number of possible safety solutions to consider. This may be part of the reason why cobots with smaller robots have been comparatively successful. Another explanation for the relative success of cobots with smaller robots is that most of the robots used in those settings are specially designed with many internal safety features, while the larger robot in e.g. the Vinnova funded Team of Man and Machine project (ToMM) project is not specially designed to be used in a cobot application.

Although uncommon in industry and academic literature, the ToMM project has shown that setups with large collaborative robots are possible. Some commercial installations with larger collaborative robots also do exist[2], mainly utilizing the heavy lifting capacity of large robots, while sharing workspace with humans. Earlier design studies covering collaborative setups with large robots have focused on designing cell layouts that make safe operation possible when utilizing these robots [1], and indicative models to evaluate these cobot cell designs have also been proposed [2]. However, these design and evaluation models have been limited to cobot assembly *cells*. In this paper we explore possible elements of a model for design of an entire production *system*, which is not limited to the *either-or* approach, but anticipates utilization of assembly cells with large robots in collaborative settings

We found that development of a cobot system design model could be of strategic importance for companies. Such a model puts humans in the center and may help companies cope with a future where it is assumed that ever more tasks continuously need to be automated to maintain competitiveness, in a way that is in line with the influential Industry 4.0 concept. However, we also found that there are several issues to consider when developing an effective cobot system design model and that optimizing such a model may be a complex task.

2. Method

To make this exploration we made the assumptions that a general production system model should generate a system that generates a system layout rapidly and cost effectively, which makes it possible to deliver production value cost-effectively over a relevant time span, and that is safe for operators. We also made the assumption that the main difference between "standard" robot system design and cobot system design is the removal of the necessity to have distinct physical separation between operators and machines with moving parts. Focusing on consequences of this removal, we have carried out a brief analysis of how production system design models may change with the introduction of large robots in collaborative settings. As studies on production system design that anticipates cobots with large robots are not commonly found in academic literature, we mainly used experiences from the ongoing Vinnova funded ToMM and SCOR (*Safety Model for Collaborative Robots*) projects, concerning assembly *cell* layout, as a basis for our *system* analysis. Based on these projects experiences we explored potential elements for a

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[2] https://www.youtube.com/watch?v=tlgKsTMmywk

system design model that anticipates large robots in collaborative settings, and how such a design model could be introduced in industries.

3. Optimized utilization of robots' and humans' specific strengths

Exploring a model for production *system* design which is anticipating cobots with large robots is relevant even though there exist suggestions for cobot *cell* design and evaluation models, as a holistic and integrated approach to production is increasingly more important. A holistic and integrated approach necessitates an organizational awareness of the challenges and opportunities cobot cells mean for the production system as a whole. Earlier studies indicate that removal of physical barriers and introduction of cobots mean two overarching design challenges: *What design methods will ensure solutions that optimize utilization of robots' and humans' specific strengths?* [2] *What design methods will ensure cost effective operator safety?* [1]. Below is a brief analysis how these challenges, mainly identified within the ToMM and SCOR projects, may translate into more detailed questions to be answered on a production system level.

With the either-or approach to industrial automation models, identifying *efficient automation levels* is relevant. With the introduction of cobots, models to design *efficient man-machine cooperation* become more relevant. Identifying efficient automation levels is often a question of weighing trade-offs between manual or automatic assembly, while maximizing cooperation benefits is a question of optimally combining human and robot strengths. A brief analysis of how to remove physical separation and combine strengths led to our suggestion for system design considerations below, which are considerations that to some degree have been covered on an assembly cell level earlier [3]:

As humans and robots have different strengths, there need to be methods to continuously identify what those specific strengths are, and how the strength relations change with the ongoing rapid technology development, e.g. within the AI field [4], and particularly within the AI sub field *machine learning* [5]. Human strengths comprise for example: Understanding of the concept "a good production result" or "production value", dexterity, fitting abilities, skill to handle flexible or soft components and ability to adapt to new situations, while robots have e.g. stronger reach, power, speed and repeatability capabilities. How can the continuous encroaching of robot capabilities on human strength domains be monitored? In this monitoring should methods to monitor the continuously improved possibilities for rapid deployment and production setting changes of automation solutions, be included.

There need to be developed methods to identify applications where cobots may be particularly productive, that is, where the combinations of strengths are most beneficial. While this analysis model may change little with time, the analysis results, however, most likely will change as fast as robot technology develops and encroach on ever more human domains.

Cobot solutions including larger robots offer more opportunities for component logistics optimization, which also increases installation complexity. There is a need to evaluate design of component logistics that takes advantage of cobot solutions, where e.g. methods for utilization of robot reach and automation of component data handling could give significant production value. This analysis also needs to ensure that advanced component logistics solutions do not increase changeover time between production settings, and hence possibly reduce production value over time. Methods for logistics cost-benefit analysis is important.

Collaborative work in absolute proximity means that there is an increased number of man-machine communication and interaction solutions possible, compared to assembly cells with a physical separation between man and machine. Methods to evaluate all these communication methods need to be developed, and to adapt the production system to handle these possible new communication methods and information flows. In this, there is a need to evaluate the usefulness and methods for robot hand guiding as a communication method, e.g. by using smart textile gloves [6].

When a distinct physical separation between man and machine is no longer needed, industrial robotics research may have much more in common with non-industrial robotics research such as research on social robots, advanced prostheses and exoskeleton research. Methods to identifying and evaluating solutions for effective human-machine interaction, originating outside of industrial settings should be relevant. Resources spent to develop methods for productive naming of robots, coloring, sound design and surface texturing may prove well used.

From the above follows also that methods for product design that takes advantage of cobot possibilities for effective assembly are important.

4. Safety in Collaborative workspace and operations

The most fundamental difference between the either-or production system design and cobot system design is that safety solutions for humans and robots working in absolute proximity must be developed. For example, different communication channels such as programmed instructions and physical instructions, e.g. through smart gloves, may lead to conflicting instructions, and methods for resolving such possible conflicts in a safe way need to be developed. Human-machine role modeling and the questions: Who? When? and How to be in charge? will be important. Another example is that with the introduction of cobots in general, and with larger robots in particular, IT-security will be even more important, as this introduction will mean that IT-security will, in a direct way, equal operator safety.

Some steps have been taken to address these and other safety considerations in a standardized way. According to ISO TS 15066 [7] collaborative operation is a state in which a purposely designed robot system and an operator work within a collaborative workspace. As noted by Krüger 2009 [8], collaborative operations that are carried out in so called hybrid assembly systems perform either handling or assembly tasks, and such systems can be divided into two groups:

- Workplace sharing systems - The operator and robot are carrying out either handling or assembly tasks independently.
- Workplace and time-sharing systems - The operator and robot are able to jointly or independently perform these tasks at the same time.

A fundamental requirement of collaborative operations is also the specification of predefined tasks and that safety through risk assessment is ensured. Robot safety standards recognizes the implementation of one or more of the following four different kinds of collaborative operations:

1. Safety rated monitored stop -- The robot stops all motion when the operator enters the collaborative workspace.
2. Hand Guiding -- The robot motion is controlled by the operator through a hand-guiding device.
3. Speed and separation monitoring -- The operator is monitored continuously in order for the manipulator arm moves at a safe speed with respect to the operator. The speed of the robot corresponds to the minimum distance between the manipulator arm and the robot.
4. Power and force limiting -- The manipulator arm is equipped with sensors so that the motion is stopped upon collision. The speed is controlled or limited so that the forces and momentum upon impact with the operator are within the limits in order to avoid injury. The velocities need to be determined during risk assessment.

The manual and manual high-speed modes are intended for programming, testing and validating the functionality of the robotic systems. Within the collaborative workspace, where the operator and the robot can collaborate to complete tasks, monitoring is needed as there is a high risk for hazards [9]. Task-based risk assessment methodology as specified in ISO 12100 [10] is the preferred method to identify, document, analyze and eliminate the risks associated with hazards. To assist in the risk assessment, the standards specifies the performance requirements for the robot as well as the equipment such as safety-rated stop and contact force limitation [7,10,11].

4.1. Cognitive issues during Human-Robot Collaboration

Assembly plants that constitutes high production rates involves repetition of the same tasks and such a working environment might affect the performance of the assembly line workers and lead to errors. That is when the tasks are manual and highly repetitive, human workers tend to make some mistakes over time. Performance can also be impacted if the tasks are highly automated and operators are mainly expected to supervise the automation machinery. Such a role is often termed supervisory control and the occurrence of errors can be attributed to the attention capacity of human beings.

The flexibility offered by modern technologies allows the designers of automation machines to develop solutions that work across many modes of operation. As supervisory control demands regular or constant monitoring of machine operation, errors associated with situation awareness such as mode error become critical [12]. As pointed out by Sarter [13], it is important for the users of automation machines to be aware of the mode of operation so that they can correct actions pertinent during the mode.

In order to ensure safety within the collaborative workspace, the speed and intent of the robot needs to be clearly defined when the robot enters the collaborative workspace until the robot moves back to the robot workspace. The state of the robot during this motion can be termed as collaborative mode and needs special attention during hazard identification and risk analysis. In order to eliminate the hazards associated with operators being unaware of the working mode of the robot, it is useful to design interfaces that conveys to the operator the state of the system. For example, as shown by Gopinath et.al [1], green light positioned at the entrance to the collaborative workspace can convey that the robot is in collaborative mode and that the operator can enter the collaborative workspace. They have also shown that the hazards associated with unintentional motion of the robot needs to be addressed using enabling switches integrated to the hand-guiding tools.

5. Cobot system design as a production strategy tool

A model for cobot production system design should ensure that the combined strengths of humans and robots are taken advantage of in a safe way. This includes at least considerations of the issues mentioned above. However, such a model should also support a long-term production strategy and our brief analysis found four strategic considerations that could be relevant for a cobot system model.

A production system model should support an innovative work climate. Developed methods for cobot communication and safety solutions should e.g. be useful as a pedagogical tool to identify innovative solutions for other types of man-machine interaction and thereby potentially further increase productivity.

It should support a response to the ongoing industrial paradigm shift from “goods and services” focus to “value” focus, which stimulates the use of new business models when carrying out automation, and other industrial projects.

It should support an inclusive work climate. Even though automation may generate production value in many ways such as improved information handling, product quality and reduced lead times, it often is perceived reduction of manual hours that drives automation efforts. This means that optimization of “standard” automation can be viewed as a question of how to best replace operators. With the introduction of the collaborative concept, automation changes from being a question of how to best *replace* operators, to a question of how to best *complement* operators. Not only may this ease possible short-term conflicts with staff, afraid of being replaced, it can also be part of a long-term strategy to handle ever faster introduction of automation equipment with ever more capacity. When “complementing” is the guiding principle, the comparative advantage of humans can then be treated as a question of how staff should continuously reduce their focus on execution of production work and increase their focus on the, perhaps "final", human skill; defining what a "good production result" is. A complementing automation strategy is also in line with the "industry 4.0" paradigm, putting humans at the center, and also reflects the fact that only one of the 270 detailed occupations listed in the 1950 US Census has since been eliminated by automation [14]. Automation has, it seems, always to an important degree been a matter of "complementing", and not replacing operators. A method for complementing system design may generate increased productivity through better techno-organizational solutions, as well as through psychological benefits.

It should also stimulate and support development of system design tools. System design models that anticipate cobot utilization could drive the development of design support tools such as simulation and design automation tools, to incorporate cobot use.

6. Indicative elements and implementation of a cobot anticipating production system design model.

We assume that an efficient production system design model should have three general basic characteristics and generate:

- A production system that delivers production value cost-effectively over a relevant time span, including continuous upgrading, and several changes between production settings and maintenance sessions.
- A system that is safe, where ergonomic safety is included
- The required system layout that is required for the above, rapidly and cost effectively.

On the basis of these assumed basic characteristics and our brief study above we suggest the elements and tasks for a cobot anticipating design model summarized in table 1.

Table 1. Suggested elements of a cobot anticipating production system design model.

Design model elements and tasks
• Comply with, or be, the main guiding tool for the production strategy.
• Define production system value over time, including value of rapid robot deployment.
• Continuously identify and update status for comparative strengths man-machine.
• Identify most relevant and productive cobot applications.
• Analyze how choices of different types of robots may impact analysis and installation resources.
• Propose, evaluate and choose safety methods.
• Propose, evaluate and choose man-machine communication solutions.
• Ensuring productive cobot information handling.
• Propose, evaluate and choose layout design, utilizing logistics, and resource efficiency potentials.
• Utilize tools as machine learning, design automation or the "learning apprentice" concept [16].
• Comply with effective standards.

We also assume that implementation of new production system design methods should complement existing system design models and not replace them. We therefore suggest the introduction method summarized in table 2.

Table 2. Suggested industrial implementation method for a cobot anticipating production system design model.

Suggested implementation tasks
• Ensure organizational awareness of cobot possibilities and that such installations require often unfamiliar, considerations regarding layout, communication and safety. Initiate educational programs. • Ensure enough resources for definition and specification of desired value from production systems. • Ensure that all automation measures are treated as part of general measures to increase productivity and production value, and not measures separated from this objective. • Introduce a company language emphasizing that automation is about complementing and not replacing. Maybe suggest how the human comparative strength will be ever less about execution of work to deliver production value, and ever more about definition and specification of this desired production value. • Expand the monitoring of research fronts to cover research of non-industrial man-machine interaction. • Initially focus on system design that anticipates the use of cobots with small robots with an already proven track record. • Ensure ability to utilize simulation, machine learning and other software tools adapted for cobot installations.

7. Conclusion and future work

Possible characteristics of a design model for production systems that anticipates utilization of large robots in collaborative settings have been explored in this paper. The exploration indicates that optimizing such a design model may be a complex task, as many new, often unfamiliar considerations has to be made, compared to when the *either-or* approach is used. In order to develop a cost-effective design model we suggest a more in depth study where the validity of our findings above is experimentally tested. This should for example include further analyses of:

- How rapidly increased opportunities for full automation impacts collaborative automation.
- Trade-offs between rapid installations of cobot cells with smaller robots, and slower installations of, potentially more productive cells with larger robots.
- Importance of using robots/tools specifically designed for cobot applications.
- Possibilities to utilize tools such as design automation and machine learning for cobots.
- Standards for installations of large robots in collaborative settings.
- Refined strategy of practical industrial implementation of cobots utilizing large robots.
- Development and execution of model test schemes.

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