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Potential advantages using large anthropomorphic robots in human-robot collaborative, hand guided assembly

Sten Grahn[a,b,*], Björn Langbeck[a], Kerstin Johansen[c], Björn Backman[a]

[a]*Swerea IVF AB, Brinellvägen 68, Stockholm 10044, Sweden*
[b]*Mälardalen University, Drottninggatan 12, Eskilstuna 632 20, Sweden*
[c]*Linköping Universty, Linköping 581 83, Sweden*

* Corresponding author. Tel.: +46-16-15-5125; fax: +46-16-15-3630. *E-mail address:* sten.grahn@swerea.se

Abstract

Collaborative robot installations often mean man-machine workspace sharing. This mode of operation can lead to reductions of tact time and work space requirements. We have analyzed potential further benefits of man-machine collaboration, where operators and powerful robots share workspace, cooperating when lifting and handling large objects. We found that this mode of operation has the potential to generate economic advantages by reducing the need for manual operators and lifting tools and by offering new opportunities for component logistics.

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Keywords: human-robot collaboration; robot safety; human-machine interface; hand-guided collaborative robot

1. Introduction

Advancements in several fields such as programming, robot sensor and control technology, force sensing, environment recognition, human–machine-interfaces and safety system technology have made it possible for people and robots to work in absolute proximity. These installations are often called collaborative robot installations. Bley, et al. [1] have shown that this mode of robot operation promise several potential benefits as it takes full advantage of robot as well as human strengths. Collaboration can reduce costs for space and safety measures as shared space is possible. Krüger et al [2] also claim that reduced tact time is possible as operation sequences can be made more efficient. They analyzed tact time reductions using a net present value calculation and found that a hybrid collaborative robot solution had an NPV that was 25% higher than a standard robot cell and substantially higher NPV than a manual solution. However, sharing workspace is a narrow way of defining 'collaboration'. A broader definition includes a mode of operation when robots and humans cooperate to hold and move objects. This mode of operation adds more parameters to evaluate when analyzing such an installation. The aim of this work was to contribute to the development of methods to compare such installations with manual assembly or "full" automation. An initial study on what to analyze when evaluating collaborating installations [3] was complemented with recent findings on possible methods to carry out the analysis. Three large anthropomorphic collaborative robot installations were evaluated with the updated scheme and it was found that the issue of full robot speed and range utilization is more relevant to evaluate compared to evaluation of small collaborative robots. It was also found that the potential to reduce cost by eliminating lifting tools, by using the robot as a lifting tool instead, is one important added benefit that separates large collaborative robot installations with small collaborative installations. Another added benefit is that the improvement potential for component logistics is larger than for smaller robot installations, as component placements can be adjusted to utilize the robot range and lifting capacities.

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2. Benefits and limits of robot installations

2.1. Benefits and limits of traditional robot installations

Traditional robot installations can offer several benefits compared to manual operation: Improved repeatability, increased precision and speed. Heavy lifting is made easy, often with a range beyond the range of a single human. Manual hours can be reduced and ergonomics improved. Traceability and general handling of information to and from the production process could also be secured easier.

However, robots still have many weaknesses compared to humans. The resources required to overcome those, limit the usability and cost efficiency of robot installations. For example, currently robots have a limited ability to perceive its surroundings, which requires costly safety arrangements in order to avoid personal injury. These safety arrangements are particularly important and costly when working with installations of large and powerful robots, as fences and light beams are required to keep humans out of the work space. However, with sufficient robot ability to perceive and adapt to a changing environment, the need for safety arrangements that keep humans out of the robot work space are no longer necessary. Robots can then be allowed to work in collaborative mode, sharing workspace with humans. In some situations, this may reduce the safety arrangement cost as fences and light beams may not be needed. This currently comes with a performance cost though, as the robot TCP speed is, by regulation, limited to 250 mm/s when humans are inside the workspace. This speed limit may, however, increase in the future.

Costs and challenges when securing handling of complex components, binge gripping, fitting and changeover between production settings may also make robot installations less cost efficient compared to manual operations as humans carry out such operations with relative ease.

2.2. General collaborative benefits and considerations

As robots and humans have different strengths, combined utilization of human and robot strengths in a collaborative robot installation, could make such an installation competitive. This is especially the case when the ability to cost efficiently carry out the challenging robot operations mentioned in 2.1 is important. Comparing manual operations, traditional robot cells and collaborative installations, though, is not a straightforward affair. The different setups require different considerations and impact many production parameters in different ways. In order to secure a 'fair' and relevant comparison and identify which solution is the most cost efficient, Grahn and Langbeck [3] developed an indicative evaluation scheme for collaborative robots. Some of the main points found relevant to evaluate in that study are briefly mentioned below:

- *Role assignment* between robot and human, see e.g. Jarasse, et al. [4] and Li et al. where they mention game theory [5] and optimization [6] as methods to approach the problem.
- *Acceptability* of these types of installations. Weistoffer, et al. [7] found for example that it is robot appearance dependent.
- *Context*. Hedelind and Jackson [8] studied benefit from a lean perspective. They found that lack of information from what caused production standstills hampered possibilities. They found that it is not necessarily a conflict between lean and automation, but that providers want closer contacts with applications to ensure maximum benefit from robots in a lean environment.
- It is important to find both the *level and type of automation* [9] that best suits the needs and requirements of the environment in which the automated equipment should be used. Säfsten et al. [10] address the concept of *rightomation*. An evaluation scheme should hence produce results that can be viewed in the light of environment requirements.
- Krüger, et al. [2] emphasize that collaboration offers several alternative *assembly sequences* that need to be evaluated in order to minimize tact time.
- *Set-up time.* Kus, et al. [11] have analyzed the requirements of small and medium size enterprises (SME). They found that one of the most important disadvantages of using robots compared to manual assembly was that reprogramming requires expert knowledge. Programming improvement has, however, led to robots that can be programmed by taking the arm of the robot and showing the robot what it should do (hand guiding). This can reduce the time it takes to integrate robots into factory operation from typically 18 months, down to 1 hour [12]. A robot equipped for collaborative hand guiding work can be programmed by hand guiding as well.

3. General large collaborative robot considerations

The evaluation scheme [3] suggesting an initial guidance on what parameters to analyze when implementing and evaluating collaboration cells, was combined with recent findings on how to carry out an analysis, mainly collected from the IROS 2015 conference in Hamburg and was applied on three theoretical large anthropomorphic robot installation cases with a payload up to 500 kg (further described below). This was in part done to identify the initial scheme limits and in part to get an initial indication on expected benefits for large collaborative robot installations.

Context and automation level considerations indicate that large robots potentially adds further benefits compared to small robots as they can also offer a solution for *heavy object lifting* and *human range limitations*. Full exploitation of these further potential benefits requires evaluation of more design alternatives compared to collaboration with small robots. These considerations led to three initial designs for a collaborative assembly cell using a large robot. The alternatives exploit large anthropomorphic robot benefits using alternative combinations of robot operation modes and manual assembly with lifting tools (MA). Current robot operation mode (CRM) with standard safety arrangements using for example fences, makes it possible to utilize max speed and range of the robot. Collaborative robot in active mode (CMa) only sharing workspace, makes it possible to utilize max range of the robot but can make max speed utilization difficult due to safety risks. Collaborative robot in passive mode (CMp) makes it possible to use the robot as a lifting tool. These different operation modes can then be combined in three main settings which all are able to carry out the same assembly operation, shown in table 1.

Table 1. Alternative robot and manual assembly combinations

Design alternative	Combination
1	CRM + CMa + MA
2	CRM + CMa + CMp
3	CMa + CMp

It was seen that potential for improved range and more *efficient component logistics*, compared to manual solutions can be utilized for all robot layouts above. Context considerations led to the insight that *utilization of full robot speed* is of limited value as the assembly cells were dependent on the *speed of the assembly lines*, for our three cases. The alternatives 1-2 would hence be less relevant as they require more space, more safety arrangement or additional lifting tools. The last layout was assumed to offer most cost efficiency opportunities and we focused on comparing this setting with a fully manual assembly solution with operators using lifting tools.

We further assumed that the three cases had the acceptability issue in common and carried out an interview study [13]. The study at two large Swedish companies involving ten operators showed that five were positive, two hesitant and three negative to robots without fences. Some of the respondents were also expressing a concern that the robots would replace them and take work from the humans. It was obvious that the acceptability issue has to be addressed. The interview study suggests an evaluation regarding whether the attitude would be different if the collaborative solution was called a *'robot-helper'* or if you had a robot *'assisting'* you, which implies another hierarchy. The study also suggests that the *use of signals* as guidance or confirmation may increase operator acceptability.

4. Specific large robot case study considerations

The Vinnova funded, Team of Man and Machine project (ToMM) aims at exploiting the potential benefits of large collaborative robot installations. We used the evaluation scheme to theoretically evaluate the three cases in this project.

4.1. Specific assembly operation case 1 – Placement of aero panels under a vehicle

In the first case a robot will be used to place aero panels under a vehicle, which is a standard component in 5-10 different variants per vehicle. The panels may also differ between vehicles. The panels are stable from a geometric point of view. The polymer panels are large but light-weight (about 4 kg). The assembly work is today performed in a non-ergonomic way with an under-up-work placement method (fig. 1). If a robot in collaboration with an operator could carry out this placement the process would be very flexible, the ergonomic situation for the operator could be improved, fewer operators would be needed and no lifting tools would be necessary. The robot is assumed to place the panel under the car body and the operator is assumed to use a handheld tool to assemble the clips. Full automation is not possible due to the complexity of high precision assembly of the clips. However, the automation level could still be evaluated as the panel fitting could potentially be done manually or automatic. If automatic fitting would be possible, no *enabling device* and no *transfer from active to passive mode* is necessary.

Context, range and *information handling considerations* show that the robot could work as a *kitting* support to the operator by selecting the right panel at the right moment. This possibility can reduce the need for production space for panel storing. A *vision system* or automatic bar code reading could keep track of the assembly stage so that the *correct part for the current model/version of the product is handled over at the correct time*. This could decrease the mental stress of the operator and ensure that correct parts are assembled.

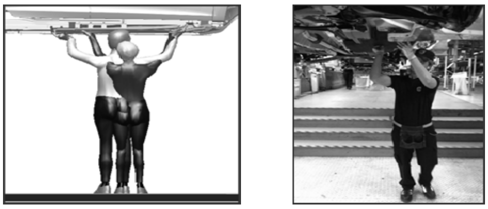

Fig. 1. Non-ergonomic placement of aero panels, requiring a specific length for operators.

4.2. Specific assembly operation case 2 – Heavy and repetitive lifting

In the second case a robot will be used as a lifting device picking and executing a desired trajectory, with the aim to assemble a heavier component and position the object in the right position in relation to guiding pins. The pins will provide a friction that is used in the assembly, which the robot must manage. Today the operation is carried out manually and the object is assembled at an angle of approximately 30 degrees to give the operator a more ergonomic position. However, this operation is still not satisfying from an ergonomic point of view. The idea of this case is to let an operator guide the robot when holding the object and then brings the object to the final position. The operator receives support from the robot to push the component over the pins with friction and a *fitting* solution is important. This means that the robot first acts as a handling device, serving the operator with the correct object. Then the robot is used as a lifting aid helping the operator placing the object in the correct position. The operator then can proceed with further operations, for example tightening screws or other parts, in a potentially optimized *assembly sequence* (see fig. 2 for assembly sequence). An enabling device, *transfer point* and *transfer method* between active and passive mode are hence important issues for this case. Manual hours could be reduced, ergonomics improved, lifting tools be eliminated and sealing quality improved. The selected object exists in 3-5 variants and requires high fitting precision and needs to be pushed with force to overcome pin friction. The complexity of automated pin fitting, and changing between gripping tools and screwing tools hinders full automation.

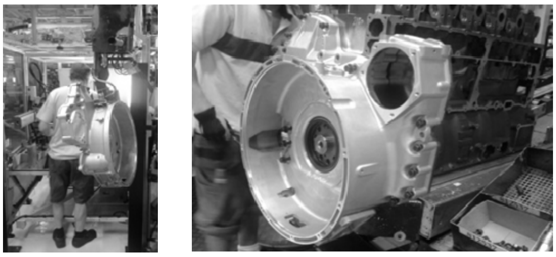

Fig. 2. Assembly sequence: Lift flywheel cover, put cover in an automated silicon applying machine and aid the assembly operator when assembling the cover on engine block by carrying the heavy load.

4.3. Specific assembly operation case 3 – Interior assembly in a truck cab

The two previous cases are, to some extent, combined in case 3. Many components that are assembled in a truck cab are large and heavy. Examples are dashboard, ceiling lining, beds and various storage drawers. These are currently assembled with one operator inside the cockpit and another operator working outside the cockpit picking up the parts with a lifting device, transferring them to the operator inside the cockpit. If a robot could perform the lifting of the dashboard from the conveyor belt, to the sealing station and then into the cab, the task could be performed as a one person task instead of a two person task. The robot application of the sealant has the potential to result in better sealant application quality as robot *repeatability* is assumed better than human repeatability. The add-on difficulty in this case, compared to the first two cases is that the dashboard is placed manually and the target *position on the belt is not well defined*, as it does not have a fixed position on the conveyor. This challenge hinders full automation, together with *complex* dashboard *gripping* and *screwing* challenges.

Fig. 3. The cockpit to be automatically lifted from conveyor belt, to sealing station and then inserted into the cab

5. Analysis

5.1. Adding and rewriting evaluation scheme parameters

The results indicate that the earlier developed evaluation scheme [3] is a useful guidance when analyzing large collaborative robot installations. However, the findings also showed that the scheme could potentially be more useful and lead to better cell optimization and more relevant comparisons with manual cells if more evaluation parameters and/or subheadings are added. The findings also indicate that several evaluation parameters should be viewed in different contexts to minimize the risk of sub-optimization. For example the issue of role assignment, from active robot mode to passive robot mode, can potentially affect programming, set-up time, the need for enabling devices, safety issues and tact time, and should be viewed within all these different contexts. In order to support a holistic analysis of all relevant evaluation parameters we suggest an updated evaluation scheme. Instead of single evaluation parameters this scheme has evaluation sections, containing several parameters to evaluate. The first two sections consider collaborative robot impact on the broader production system, while the later sections are concerned with more local production cell considerations. Some parameters are present in more than one section:

Assembly system impact. A large robot usually has a larger range and lifting capacity compared to a human. Utilizing the range could e.g. make it possible to find more efficient *component logistics* systems, compared to manual assembly.

Communication and information handling. Robots can receive and transmit information to and from the larger production system and collaborative humans. This can e.g. be used for choosing correct components and making collaboration smooth. As our cases indicate, there should also be subheadings: information *from* and *to* the *larger system*, as optimization of information handling most likely means different things dependent on if the robot or the human is handling the information. It should also have subheadings *to* and *from* humans.

Acceptability and safety. Current safety arrangements have to be used when programming the robot for CMa. Current lifting tool safety levels have to be used to make sure that the robot does not drop heavy components. The interview study indicates that the issue is important and that *wording* as well as various *technology* solutions could be used to increase acceptability (see table 1). Other studies have shown that *trust* is crucial for operational efficiency and that robot performance, e.g. *reliability*, *false alarm rate*, *failure rate*, etc, has relatively high impact on trust [14]. Methods for measuring trust have also been developed [15]. Regarding appearance there are studies showing that machine like or human like appearance can have different impact on likability depending on setting [16]. A safe solution for transfer between CMa and CMp must be found. The robot must come to a safety stop according to ISO 10218-2 standards when in CMp. A design of the enabling device that can ensure CMp compliant with ISO 10218-2 must be found. Safe speed and acceleration levels for CMp must be found.

Automation level. Our findings indicate that there should be several subheadings to analyze: *Logistics automation*, *automation of information handling*, *lean production*, *utilization of full robot speed*, need for *active mode* and *passive mode*, *transfer point* from active mode to passive mode, *transfer method*, *enabling device* and *set-up time*. These subheadings highlight the need to analyze all aspects of the production system and to evaluate the consequences of all combinations of alternative robot operation modes, use of manual tools and transfer points.

Assembly sequence analysis should consider optimal tact time design, including transfer points, as well as safety issues.

Setup and programming should consider setup speed, cost and necessary programming skills. Limited programming is needed for CMp since the robot is hand guided, indicating that operators with limited programming knowledge can operate the cell with a sufficient safety level. The transfer point from CMa to CMp will decide the type and level of programming skills needed.

5.2. Practical implementation and evaluation

Numerous methods and tools to carry out the practical implementation and evaluation of collaborative cells have been discussed.

At a 2015 IROS conference workshop it was demonstrated that only 1/3 of robot system costs come from the robot cost. A comparatively high technology utilization level could hence be considered and kitting and high resolution on force sensing and control were mentioned possibilities to be used for cell optimization. At the 2015 IROS Safety workshop were also e.g. included discussions regarding:

- Using *Kinect* cameras to get depth information in order to avoid collisions.
- Combining *force control* methods and *pain* studies to identify what type of control is required to stay below a pain threshold if there is a collision.
- A *pre collision control strategy* could minimize injuries [17].
- Methods to *predict locations* of humans and robots in order to avoid collisions.
- Cover robot with *soft skin* to reduce risk of collision injuries [18].

Evaluation of all these methods and how they could be combined [19] should be considered for safety reasons. They could also be considered as means to make the transfer from active mode to passive mode, cost efficient. Transferring methods should also include an analysis of efficient handover methods [20] [21] and methods to reduce robot jerk, making the transfer smooth [22]. It has also been suggested that the robot and human should preferably communicate by gestures [23]. Issues such as safety consideration, transfer point and method also affects automation level considerations. So does programming and it has been shown that if it is possible to program the robot by guiding the robot arm the set-up time could be reduced significantly [11]. Other rapid programming methods have also been developed. The IROS 2015 discussed e.g. *programming by demonstration* where robots could be used for automatic evaluation of an assembly and copying of a human performing a task. *Skill learning by demonstration* was also discussed, which is a trial and error method where a robot could perform a task and based on the feedback, robot performance was shown to improve. The development of the evaluation scheme is shown in table 2. In order to identify whether manual assembly or a collaborative robot cell is the most cost efficient solution for a company, a holistic approach must be used. We suggest that parameters relevant for each section below are analyzed for the different assembly methods. Since some parameters are relevant for more than one section this means that these parameters must be analyzed several times in different contexts to enable relevant cost efficiency comparisons for the different assembly methods. "Possible Considerations" are suggestions on issues to consider when analyzing the parameters. For example many component variants may give a robot solution a competitive edge as one can assume fewer erroneous component selections with robot solutions. If object recognition and expensive vision systems are required, this may give a manual solution a competitive edge.

Table 2. Sections and considerations

Sections/Parameters	Possible Considerations
Assembly system impact	
Component logistics	*No of component variants?*
	Size of components?
	Kitting?
	Component identification method?
	Logistics automation?
Information, communication	
Cell-Production system	*Info type?, Protocol?*
Human- cell?	*Text and writing?*
Robot-human?	*Light, gestures, speech?*
Acceptability and safety	
Wording	*'Assistant'?*
Technology	*Human-like?*
	Kinect cameras?
	Force control, resolution?
	Pre collision control strategy?
	Location prediction?
	Air bags?
	Light signals?
	Passive mode speed?
	How avoid dropping heavy objects?
	Light beams/fences necessary?
Trust	*Robot performance?*
Automation level	
Information handling	*To and from cell?*
Robot speed	*Lean production?*
Active mode	*Passive mode avoided?*
Passive mode	*Enabling device design?*
Transfer point	*Set-up time?*
	Complex gripping, fitting, handling?
	Undefined object positions?
	Repeatability need?
Transfer method	*Simulation?*
Vision system	*Object recognition necessary?*
Component orientation	*Optimal handover orientation?*
Jerk	*Minimization?*

Assembly sequence	
Safety issues	
Transfer points	*Tact time?*
Set-up and programming	
Arm guiding	*Transfer point?*
	Special knowledge required?
Programming by demonstration	*Programming Cost?* *Programming Time?*
Skill learning by demonstration	

6. Conclusion and future research

Our study indicates that lifting tool elimination, improved component logistics, improved ergonomics and reduced hours are the biggest improvements a large robot collaborative cell could offer, compared to manual assembly. However, in order to make a relevant comparison between a collaborative assembly cell and manual assembly both those alternatives first have to be optimized individually. Our study indicates that many different layouts of a production system containing collaborative robot cells are possible. Challenges include e.g. choices of information handling, safety measures, and assembly sequences. Optimization of such a cell requires consideration of many different parameters and we have produced an extension of en earlier evaluation scheme to guide cell implementers and operators when making optimization and evaluation attempts. A collaborative robot test cell has been built and preliminary results indicate that the suggested scheme will be useful for analysis of the cell. Further development of the cell and practical implementations of two of the three described cases will be evaluated to verify the evaluation scheme usefulness.

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