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A Method to Distinguish Potential Workplaces for Human-Robot Collaboration

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Abstract

The high dynamics of globalized markets and their increase in competition, as well as the demographic changes in western countries causing an increasing shortage of skilled personnel are resulting in major challenges for production companies today. These challenges relate in particular to the processes of assembly forming the last process step in the value chain due to its high share of manual labor. Collaborative assembly, which is characterized by immediate interaction of humans and robots, utilizes the strengths of both partners and is seen as an opportunity to achieve a higher level of flexibility in assembly just as well to support and relieve people of for instance non-ergonomic tasks through automation at work. Although almost every robot manufacturer already has collaborative systems in its product portfolio, these are not yet widely used in industrial production. This might have a variety of reasons, such as the fear of a risky investment or the lack of expertise within the company related to collaborative systems. This article shows a conceptual method that helps companies implementing human-robot-collaboration in their production more quickly and with less implied risk, thus addressing the forthcoming challenges. As a first step, companies must be qualified to make a suitable selection for a possible collaboration scenario. To achieve this, they need a tool to analyze and to evaluate their production processes according to their suitability for human-robot-collaboration. An important feature for an easy and effective use is that the process is formalized so that employees of companies can quickly and easily analyze different processes. The necessary criteria and procedures are developed accordingly and are integrated into the selection method. The main goal is to give the company a recommendation which of their processes are most suitable for human-robot-collaboration, so that they can be used effectively in their production.

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Keywords: augmented reality, intuitive robot programming, human-machine-interaction

1. Introduction

In today's world, manufacturing companies face a change in the demands placed on them. In addition to the usual targets such as production costs and quality, characteristics such as speed and changeability are becoming increasingly important [1]. The number of product variants continues to increase and at the same time the product life cycle is shortened due to the increasing speed of innovation [2]. This results in a trend from large to flexible and medium-sized quantities as well as the striving for a growing quality of the products [3].

Traditionally, the production of large quantities has been implemented economically by fully automated production. Among other things, it is characterized by high productivity and consistent product quality [4]. The rigid interlinking and the special orientation of the means of production to a particular activity, however, result in extremely low flexibility with regard to product changeovers. The increasing variety of variants and decreasing batch sizes mean that automated assembly is often not economically feasible due to time-consuming setup procedures. The application possibilities of conventional industrial robots, which are often used in production due to their flexibility, also reach their limits. Time-consuming reprogramming is required for each variant change.

Companies must therefore adapt to these changing market conditions in order to remain internationally competitive. Unfortunately, the automation required for this goal leads to limitations in flexibility. However, human perception and decision-making are required for complex production steps, so these processes are still carried out manually today [1].

One way to increase efficiency in this situation is the human-robot collaboration (HRC), in which humans and robots work directly together at one workplace. The human robot collaboration, as an example of a hybrid assembly system, lies between manual and automated assembly with its variety of variants, productivity, quantity and flexibility [5]. In addition to

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the possibility of designing economic working place systems by means of an appropriate distribution of work, the HRC can also improve the ergonomics and age-appropriate design of the human workplace with regard to the demographic change in some countries [6].

Many research groups are therefore concerned with the optimal planning and design of human-robot collaborations. Thus there are already first approaches for various design criteria such as the cell structure [7], the safety concepts [8], the improvement of ergonomic conditions [9] but also of used path planning algorithms [10] in HRC workcells.

There are many different interpretations and definitions of human-robot collaboration in literature [11]. In this work, we will subdivide the different workplaces into coexistence, cooperation and collaboration. These subdivisions can be defined according to the task, workspace and workpiece. The term coexistence describes the existence of human and robot in a shared workspace. The simultaneous but independent work is carried out at a safe, collaborative workplace without the need for safety guards between humans and robots [11]. Human-robot cooperation describes a concept in which work actions and the necessary information are exchanged between humans and robots. The participating partners have a common workstation, which eliminates the strict separation of the workstations of the robot and the worker. However, there is a temporal separation of the processing, so that both partners do not interact with each other at the same time. Collaboration refers to a situation in which humans work directly with the robots at a common workplace without separating safety installations. The interaction partners carry out a task together, so that a contact between them is possible at all times [11].

This paper presents a procedure to initially check existing or future workplaces for their suitability for HRC. The procedure is based on an assignment of work tasks between humans and robots within the workplace. This fact was named among others by Tsarouchi [12] as challenge of HRC. In order to create a better comparability between workplaces and thus to get a better choice of a possible process, new characteristic values are developed. These parameters should give an overview of how much people and robots work together in a process.

At the beginning of the paper, some industrial applications with different characteristics of human-robot interaction are presented. Subsequently, a concept for a general guideline for the implementation of human robot collaborations will be presented. The potential check is presented in the following chapter. Based on a summary, an outlook on future work is given.

2. Human Robot Collaboration in Industrial Environments

Human robot collaborations are seen as a tool for managing the before mentioned challenges. This is also illustrated by the fact that large manufacturers present their modern production lines in which people and robots work collaboratively on their trade fair stands and social media platforms [13], [14], [15]. By demonstrating this modern technology in their own production facilities, the manufacturers hope not only to benefit from the advantages of semi-automating manual work processes, but also to have a good publicity impact. In most cases, however, this is not a human-robot collaboration with regard to our definition. Often, a robot that is capable of collaboration is used instead of a conventional robot with safety fence without making any changes to the production process [16]. Consequently, there is no real cooperation between human and machine in the same workspace. Instead, both parties work in their own workspace and the interaction is limited to a small transfer area. Volkswagen, for example, is also using this type of cooperation to assemble delicate glow plugs in its engine blocks [17]. The use of a collaborative robot in this application offers several advantages, such as compact integration into the existing production process and improved ergonomics. Nevertheless, the robot is not used collaboratively. The operator and the robot work at separate stations of a conveyor system where their workspaces overlap only slightly. In contrast, however in research there are already some examples of successful collaboration between humans and robots [18], [19]. Additionally the big robot manufacturers have presented many possibilities to let a robot collaborate with a human, also the shown examples often appear very forced and economically not meaningful [15]. This is mainly due to the great difficulties caused by the robot's limited handling and sensoric capabilities for possible applications [20]. As a result of the high technical and social complexity of a collaborativ application, many of the users require assistance in the selection and design of a suitable application. Furthermore, a method is required to facilitate the planning of a human machine collaboration in an industrial environment.

3. Concept of Introduction

As these applications show, some users of robotic systems are already trying to use human-robot collaborations in their companies. However, cooperation is often limited to the handover of individual parts. Symbiotic cooperation, as which HRC is considered, has only been implemented in very few applications. A possible approach is the local and temporal overlap of workspaces. According to DIN ISO 10218 [21], a force and power limitation is needed. For this purpose, robotic systems must be used which can actually detect or prevent a collision. The reasons for this can vary widely. For example, many companies are uncertain about the precise planning system. Safety aspects in particular are regarded as critical, since employees must not be injured under any circumstances. In addition, there are also challenges in the area of the further structuring of workplaces. The technological characteristics of the individual systems must be adapted to the respective application. In addition, there are the legal standards and guidelines which must be taken into account. Another point is the acceptance of the employees towards the collaborative systems. Only accepted systems are going to be used by employees in production, which increases productivity. In order to support companies in meeting these challenges, our research project *SafeMate* pursues the approach of developing a guideline that can be applied in any industry. We have combined the sub-processes required for this in a general structure (see Fig. 1).

Based on a potential check, existing jobs are gathered, evaluated and checked for their suitability for HRC. Based on the assembly priority graph and a time analysis, new concepts for the process flow are then created. The processes are designed using a technology database and the relevant standards and guidelines. The technology database contains the state of the art with regard to commercially available hardware. In addition

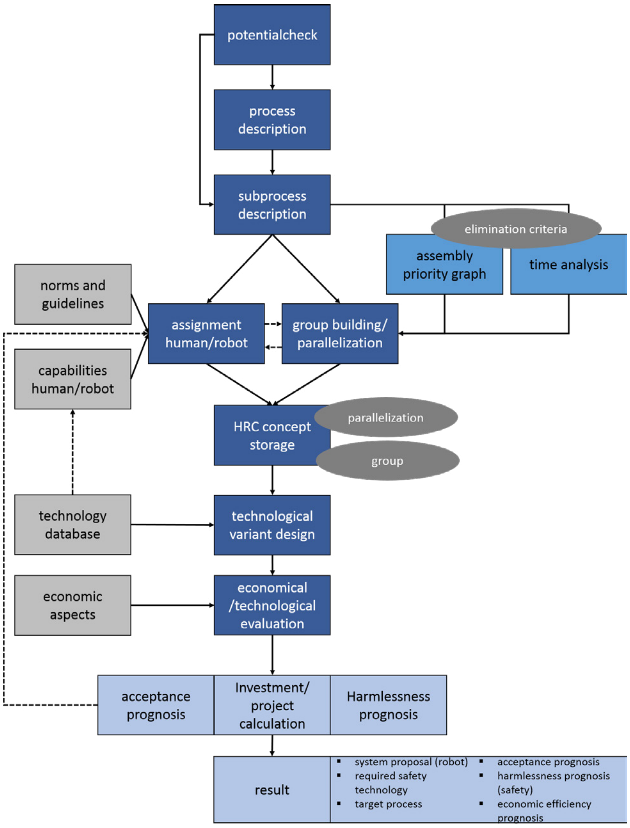


Fig. 1. Concept of a general implementation process for HRC workstations

to the collaboration-capable robots, sensory systems for generating co-operations and coexistence are also listed. Finally, the developed concepts are evaluated technologically and economically in order to make a statement about the suitability of the concept for the application. From a technological point of view, aspects such as process reliability, flexibility and material handling are taken into account. Acquisition costs, amortisation periods and possible manufacturing costs are also important criteria for the economic evaluation, so that production companies have a good basis for decision-making. The following points are the result of this general process:

- system proposal (robot)
- required safety technology
- target process
- acceptance prognosis
- harmlessness prognosis (safety)
- economic efficiency prognosis

The elaboration of the individual phases is now part of the project. For this purpose, we proceed strategically in such a way that we begin with the first process of potential analysis, as it has a major impact on the subsequent processes. This is presented in the following section.

4. Potential Check for Possible HRC Applications

The goal of the potential check is to quickly obtain an overview of whether a process is suitable for HRC or not. The user should be able to get an overview of where the critical points at existing or future workstations are in regard to possible HRC applications with the least possible effort. For this purpose, a two-stage guideline is implemented in which criteria are queried and examined for their suitability with regard to HRC. The two-stage guideline is designed in such a way that in the first part, simple questions generate a first overview of the application. In the second step, the application case is evaluated in more detail. The focus is on the individual activities and their possibilities for automation (see Fig. 2). The first part is based on a questionnaire to determine a general potential for collaboration between humans and robots in the application to be evaluated (similar to an approach of the Fraunhofer Institute for Production Engineering and Automation (IPA) in Stuttgart). In our approach, we first ask questions about the enablers and inhibitors to HRC implementation with regard to the properties and restictions of the existing applications. Based on this, a recommendation is made to take a closer look at the process or better to analyze another one. This may be due to the fact that the system was found to be more suitable for purely manual implementation or for full automation. The result can be used as the basis for a future HRC implementation. Subsequently, the sub-processes are analysed in more detail in the second part and examined with regard to their suitability for HRC. Individual tasks are evaluated by a user in this process. Key figures for a better comparison between the workplaces are determined. This includes in particular the prior experience and internal actions of companies.

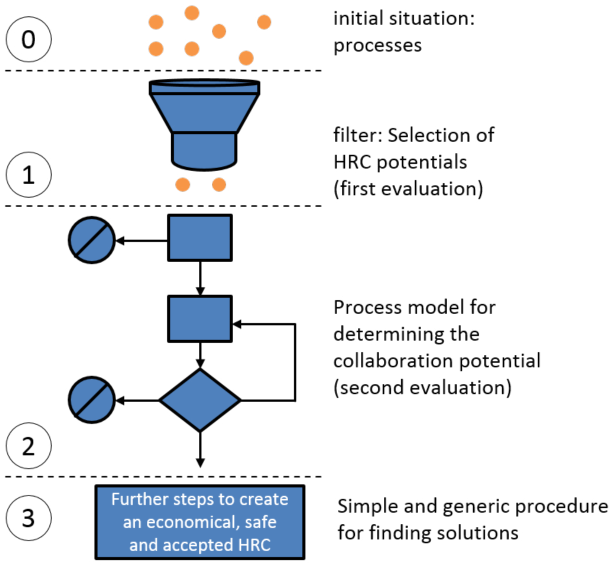


Fig. 2. Concept of a two-stage potential check

After and between both process steps of the potential analysis, it is possible to abort the further process. This is to prevent avoidable effort if no particular suitability can be determined at an early stage. If a potential is identified, the guideline for the design of economical, safe and accepted HRCs is continued.

4.1. First evaluation

In the first step of our approach, we focus on enablers and inhibitors of HRC systems. Enablers and inhibitors mean the properties or boundary conditions of processes that influence the suitability for human-robot collaboration. The individual properties have arisen both from the IPA's potential detail check and from discussions with companies experienced in HRC. The experience gained by the companies is based on the implementation of use cases in various manufacturing industries with different types of collaboration (coexistence, cooperation, collaboration). The challenges can be summarized in the following criteria:

- cycle time and process speed
- ergonomics
- material composition and supply (high risk)
- positioning accuracy
- tools
- skills
- workplace size
- variety of variants and work sequence
- special boundary conditions/environments (high risk)

These subject areas are assessed by the user so that a recommendation for an action can be determined with regard to suitability. For most criteria, common methods of analysis can be used which have already proven their effectiveness in automated systems. HRC specific criteria, such as "skills" or "tools", can only be determined in terms of quality and given application. Cycle times and required speeds are important characteristics in terms of feasibility and economic efficiency. In collaborative operation, i. e. with force and power limitation, the speed of a robot is severely limited. This means that many processes that initially possess a potential can no longer achieve the required cycle time.

Ergonomics provide an important motivation for the implementation of HRCs. Companies often recognize HRC as a technical opportunity to improve ergonomic conditions. These can have both physical and psychological origins. The focus is on heavy loads or monotony in particular.

However, important criteria that must also be taken into account in conventional robotics are the material properties and the availability of the components. If the user of robot systems wants to dispense with additional sensors, an accurate supply of components is required. This is the only way to ensure that the robot can pick up the components correctly and place them again at the appropriate assembly position.

The required positioning accuracy is of particular interest when selecting the implementation concept. Collaborative robots often have a lower repeatability accuracy than conventional robot systems. For this reason, a force and power limitation may not be possible and conventional systems with additional sensors may have to be used.

The tools contained in the process are relevant insofar as these parts must not be guided by the robot if they can injure human beings. This must be taken into account in the planning process.

"Skills" means the knowledge of the existing employees in relation to HRC. For the design of HRC workplaces, skilled employees are still needed at the moment, because in contrast to conventional systems, other criteria like additional standards or guidelines, must be taken into account. These skills must either be worked out in a time-consuming manner or new employees already having the knowledge must be hired. Furthermore, employee acceptance of HRC systems is more predictable when systems are already in use in the prodcution of a company. Acceptance of HRC systems is important because they can otherwise be rejected by employees, which contradicts effective use.

Workstations must not exceed a certain size, since robots capable of collaboration usually have a limited workspace and are therefore not intended for handling long distances.

A high number of variants in production can lead to the fact that HRC systems cannot be used sensibly. Particularly when gripper changes become necessary in the process, the cycle time required can often no longer be maintained. On the other hand, HRC systems can also support the production of a large number of variants. This is always the case if the robots do not have to be retrofitted after each component, but can carry out the task for a longer period of time. In the subsequent conversion to another product, however, the robot can react very flexibly to changing requirements by carrying out a different task without any major adjustments.

In the area of "special boundary conditions", environmental conditions of the workplace or production are primarily questioned. Very warm environments or workplaces with EMC irradiation have to be looked at and evaluated.

In addition, the actual motivation of the project is interesting for the first evaluation. For example, if the ergonomic improvement of a workplace or an increase in quality aspects is absolutely necessary, the economic efficiency of the system can be of subordinate importance.

Under certain circumstances, it may only be possible to set up a safe HRC system with great effort. Since the implementation of these workplaces usually entails high economic risks, high risk criteria are defined. This prevents too much work from being invested in determining further potential. These criteria include, for example, the handling of cutting tools by a robot, since the risk of injury for the worker is too high (part of "material composition and preparation"). Even special boundary conditions such as warm ambient conditions and highly flexible materials can make the integration of a conventional HRC system more difficult. With these "high risk" criteria, it is not possible to plan an HRC system with little effort.

At the end of this evaluation step, there is the possibility to terminate the process and examine further workstations. This may be due to the fact that no or only a limited suitability for HRC has been found or even full automation is possible. In the case of an existing potential, the process must be considered in the second step.

4.2. Second evaluation

After a potential for the workplace in question has been identified, it is investigated in a second step. The process is divided into its sub-processes so that individual activities can be evaluated. The developed system for the methodical determination and evaluation of HRC application potentials is based on a procedural model, which is presented in Figure 3. The guideline essentially consists of nine steps. The first three steps are independent of the observed process and are only carried out once per company to consider the respective needs. Steps four to nine, on the other hand, are process-dependent steps and are conducted specifically for each process (see Fig. 3). In the first step, you define evaluation criteria to which different characteristics are assigned. The criteria are used for a multi-stage decision as to whether humans or robots are better suited for carrying out an assembly operation. The definition of evaluation criteria is based on methods of Beumelburg, Deutschlander and

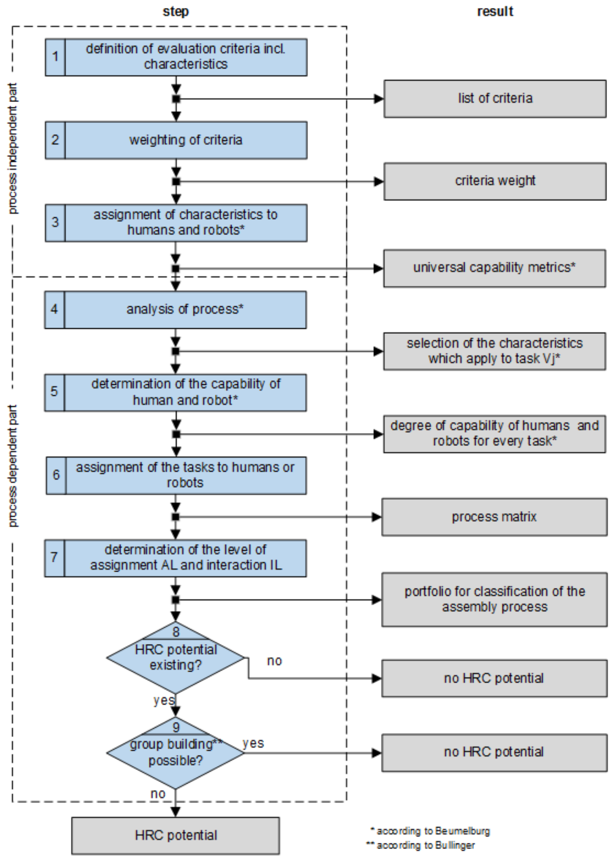
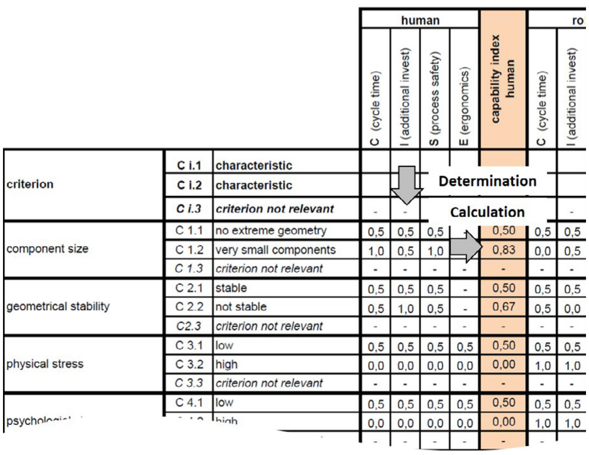


Fig. 3. Stages of the second evaluation

Ross which in their works have dealed with the topic of assembly planning [22], [23], [24]. Examples of evaluation criteria include the possibility of gripping the object, required joining accuracy, accessibility of the joining or gripping point or physical/psychological loads for the worker. The list can be created individually by the user (see Fig. 4). In the second step, the



			human					ro	
			C (cycle time)	I (additional invest)	S (process safety)	E (ergonomics)	capability index human	C (cycle time)	I (additional invest)
criterion	C i.1	characteristic							
	C i.2	characteristic			Determination				
	C i.3	*criterion not relevant*	-	-	Calculation				-
component size	C 1.1	no extreme geometry	0,5	0,5	0,5		0,50	0,5	0,5
	C 1.2	very small components	1,0	0,5	1,0		0,83	0,0	0,5
	C 1.3	*criterion not relevant*	-	-	-	-	-	-	-
geometrical stability	C 2.1	stable	0,5	0,5	0,5	-	0,50	0,5	0,5
	C 2.2	not stable	0,5	1,0	0,5	-	0,67	0,5	0,0
	C2.3	*criterion not relevant*	-	-	-	-	-	-	-
physical stress	C 3.1	low	0,5	0,5	0,5	0,5	0,50	0,5	0,5
	C 3.2	high	0,0	0,0	0,0	0,0	0,00	1,0	1,0
	C 3.3	*criterion not relevant*	-	-	-	-	-	-	-
psycholo[illegible]	C 4.1	low	0,5	0,5	0,5	0,5	0,50	0,5	0,5
	[illegible]	high	0,0	0,0	0,0	0,0	0,00	1,0	1,0
			-	-	-	-	-	-	

Fig. 4. Definition of evaluation criteria

previously determined criteria are weighted. The relevance of the criteria for the assembly processes of the respective product is determined. The evaluation helps to integrate the company's requirements more closely and to better reflect the respective relevance for the process or product. In the third step, the skill indices are determined according to Beumelburg [22]. To determine the capability index, a comparative evaluation between human and robot is carried out with regard to cycle time (EC), additional investment (EI), process safety (ES) and ergonomics (EE). The evaluation is based on the scale 0, 0.5 and 1, which corresponds to the attributes "worse","equivalent" and "better". The ability ratios for the human or robot are calculated according to the following equation:

$$E_{total} = \frac{E_C + E_I + E_S + E_E}{4} \tag{1}$$

The ability numbers for humans and robots always add up to 1. Once the process-independent part has been completed (steps 1-3 of Fig. 3), the process-dependent part that has to be executed for each process again. The assembly process under consideration is first divided into useful partial operations. In step four, a selection of the relevant criteria is made. This means that it will be checked which of the criteria defined in the first step actually applies to the subprocess and which characteristic value exists (e.g. see example in Fig. 4 "component size": no extreme geometry/very small components/criterion not relevant). In the fifth step, the suitability of the sub-process for humans resp. robots is determined on the basis of the previously determined weighting of criteria and the capability index. This suitability level is calculated for each sub-process. In the sixth step, the actual assignment between humans and robots is carried out for all subprocesses. The basis for the assignment is formed by the previously determined criteria and known process restrictions. Afterwards, the determination of an assignment level "AL" and an interaction level "IL" is carried out in the seventh step. These values should provide an opportunity to evaluate the cooperation. Both figures can have a value between "0" and "1" (see Fig. 5). "AL" indicates

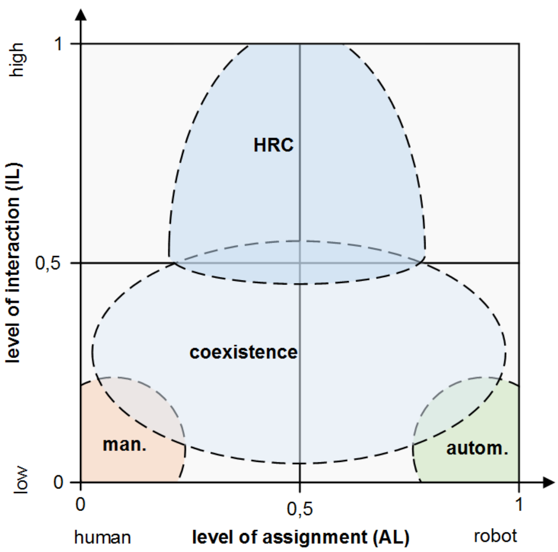


Fig. 5. Classification of workplaces in relation to the level of assignment (AL) and level of interaction (IL)

how many sub-processes have been assigned to the robot or worker. An "AL" of 1 would mean a complete transfer of the processes by the robot, while 0 means a purely manual execution. "IL" defines how often partners interact with each other. 1

would mean that the individual sub-processes are executed alternately by the robot or the worker. This results in a portfolio with the application areas of manual assembly, fully automatic assembly, human robot coexistence and human robot cooperation. Step eight examines whether an HRC application potential exists. For this purpose, the determined values for "AL" and "IL" are compared with the values in Figure 5. In step nine the user checks whether the sub-process steps can be shifted to get larger "manual" or "automatic" groups. If this is the case, a human-robot coexistence can also be implemented instead of a human-robot cooperation, since block formation reduces the value "IL". This can bring advantages in the implementation of new system, which can also be seen in the high number of already implemented coexistences compared to the collaborations in production environments.

The presented procedure is currently carried out in the form of a self-calculating table. The user is guided through the individual steps by instructions. With this two-stage guideline, the user is given an indication which workstations have HRC potential. Furthermore, depending on the allocation of the work contents, recommendations are made with regard to the type of implementation (coexistence, cooperation, etc.).

5. Conclusions and Outlook

This paper presents a concept for a general approach to simplify the implementation of HRC workstations. Some of the industrial applications presented show that robots capable of collaboration are not used in collaboration, but only carry out automated activities without a protective fence. In order to increase the number of collaborations in production environments and thus to benefit from the systems, a guideline for the simple design of workstations is presented. The potential check, which is the first part of the procedure, is described in more detail. In a first step, workplaces are quickly examined for their suitability as HRC application based on established criteria. Should this step reveal the absence of HRC potential or even full automation is conceivable, the process can be aborted and a new workstation can be examined.

In the second step, the process is divided into sub-processes and the suitability for (partial) automation is examined. These sub-processes are evaluated by the user in relation to the respective application. This results in the two values "degree of assignment" and "degree of interaction", which are an indication of the ability to collaborate. These two values are then used to classify the assembly process in a portfolio.

In further work, this two-stage procedure will be worked out in more detail. In addition, a software tool is to be developed at the end that guides the operator through the potential check. This can be helpful in identifying a suitable workplace. Furthermore, the other sub-processes of the overall concept have to be worked out, so that an integrated system is designed, which supports companies in the implementation of HRC workplaces. These should also be integrated into the software tool.

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References

[1] Abele, E., Reinhart, G.. Zukunft der Produktion: Herausforderungen, Forschungsfelder, Chancen. 1. Aufl München: Carl Hanser 2011;.
[2] Stengel, D.. Optische Arbeitsraumüberwachung zur sicheren und effizienten Mensch-Roboter-Kooperation. Sierke Verlag; 2015.
[3] Lotter, B.. Einführung. In: Montage in der industriellen Produktion. Springer Berlin Heidelberg; 2012, p. 1–8.
[4] Matthias, B., Ding, H., Forschungszentrum, ABB AG, . Die Zukunft der Mensch-Roboter Kollaboration in der industriellen Montage. In: Conference Paper, Internationales Forum mechatronik. 2013,.
[5] Lotter, E.. Hybride montagesysteme. In: Montage in der industriellen Produktion. Springer Berlin Heidelberg; 2012, p. 167–193.
[6] Schraft, R., Helms, E.. rob at work-assistenzroboter als helfer in der produktion. Automatisierungstechnische Praxis, 45 2003;2:67–72.
[7] Tsarouchi, P., Spiliotopoulos, J., Michalos, G., Koukas, S., Athanasatos, A., Makris, S., et al. A decision making framework for human robot collaborative workplace generation. Procedia CIRP 2016;44:228–232.
[8] Michalos, G., Makris, S., Tsarouchi, P., Guasch, T., Kontovrakis, D., Chryssolouris, G.. Design considerations for safe human-robot collaborative workplaces. Procedia CIRP 2015;37:248–253.
[9] Faber, M., Mertens, A., Schlick, C.M.. Cognition-enhanced assembly sequence planning for ergonomic and productive human–robot collaboration in self-optimizing assembly cells. Production Engineering 2017;11(2):145–154.
[10] Werner, T., Riedelbauch, D., Henrich, D.. Design and evaluation of a multi-agent software architecture for risk-minimized path planning in human-robot workcells. In: Tagungsband des 2. Kongresses Montage Handhabung Industrieroboter. Springer; 2017, p. 103–112.
[11] Spillner, R.. Einsatz und Planung von Roboterassistenz zur Berücksichtigung von Leistungswandlungen in der Produktion; vol. 296. Herbert Utz Verlag; 2015.
[12] Tsarouchi, P., Makris, S., Chryssolouris, G.. Human–robot interaction review and challenges on task planning and programming. International Journal of Computer Integrated Manufacturing 2016;29(8):916–931.
[13] Kuka systems and kuka industries, human robot collaboration in body construction. `https://www.youtube.com/watch?v=LdB67SPEpCw`; (17.11.2017).
[14] automatica 2016, human-robot collaboration. `https://www.youtube.com/watch?v=TxYT3Z9_3Wg`; (17.11.2017).
[15] Audi Corporate Communications - Taner, S., . Human-robot cooperation: Klara facilitates greater diversity of versions in production at audi. 2017.
[16] Universal robots - easy automation with collaborative robots. `https://www.youtube.com/watch?v=pIcxOGo7ieU`; (17.11.2017).
[17] Staff, R.. Universal robots' ur5 goes to work for volkswagen. robotics business review 2013;.
[18] Robla-Gomez, S., Becerra, V.M., LLata, J.R., Gonzalez-Sarabia, E., Torre-Ferrero, C., Perez-Oria, J.. Working together: A review on safe human-robot collaboration in industrial environments. IEEE Access 2017;.
[19] Makris, S., Tsarouchi, P., Matthaiakis, A.S., Athanasatos, A., Chatzigeorgiou, X., Stefos, M., et al. Dual arm robot in cooperation with humans for flexible assembly. CIRP Annals 2017;66(1):13–16.
[20] Hayes, B., Scassellati, B.. Challenges in shared-environment human-robot collaboration. learning 2013;8(9).
[21] DIN EN ISO 10218-2: Robots and robotic devices – Safety requirements for industrial robots – Part 2: Robot systems and integration. 2012.
[22] Beumelburg, K.. Fähigkeitsorientierte montageablaufplanung in der direkten mensch-roboter-kooperation. Ph.D. thesis; IFF Stuttgart; 2005.
[23] Deutschländer, A.. Integrierte rechnerunterstützte Montageplanung. Hanser; 1989.
[24] Ross, P.. Bestimmung des wirtschaftlichen automatisierungsgrades von montageprozessen in der frühen phase der montageplanung, iwb forschungsberichte. Ph.D. thesis; IWB München; 2002.