Systematic Planning Approach for Heavy-Duty Human-Robot Cooperation in Automotive Flow Assembly

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Abstract—**Human-robot cooperation is a new approach to meet the rising challenges of the automotive industry by enabling a higher proportion of robots in the assembly process and, thus, saves costs and increases efficiency in the context of Industry 4.0. This paper outlines a method for the planning of heavy-duty (load 90-300 kg) human-robot cooperation in automotive flow assembly to provide a structured framework for concept planning and to evaluate the early planning phases to gage whether the application can be used efficiently. The basic principles and insights of this paper are the result of a review of the literature as well as interviews with experts in automotive production and robotics technology. The method is based on an iterative approach containing a "safety concept," "workplace," and "working procedure" modules. A further aspect of the paper is concerned with the concept's evaluation in the early phases of the planning process with the inclusion of economic and ergonomic indicators. These indicators aim to ensure efficiency and profitability by avoiding excessive preparation costs due to ineffective application. The method has been applied to a practical case in the assembly line of an automotive OEM.**

Index Terms—**Automotive, cooperation, flow assembly, planning, heavy-duty robot, human-robot**

I. Introduction

Automotive manufacturers are subjected to highly dynamic market conditions. Given the demand for highly individual products from their customers, companies react by raising product diversity, which leads to fierce competition and cost pressure in the market. This profound transformation influences the manufacturing process massively. Due to the manufacturers' strategy of increasing product complexity while decreasing the cycle time for the launch of their new products, they are forced to design cheap and efficient production processes [1], [2]. Another challenge faced by companies is demographic change. In industrial nations such as Germany, the population is aging slowly, which leads to an older working population [3]. Automotive companies need to take measures to sustain the performance and health of their employees [4], given the fact that a lot of the members of staff who work in production have already reached their performance limit [5].

Regarding these aspects, it is necessary for companies to create a low cost and flexible workspace design, which can adapt an automotive manufacturing process to changing conditions. The industry aspires for a higher degree of automation, especially when it comes to high volume production. While this is a common approach in body manufacturing, the degree of automation in the assembly process still remains at a low level [6], [7]. Automated systems, depending on their given boundary conditions, are often insufficient in terms of their flexibility, which results in high investment costs that may not be paid off quickly enough. Furthermore, complex automated processes are susceptible to failure, which causes reduced availability combined with production downtime due to the rigid flow principle of the assembly lines [8].

In the context of Industry 4.0, companies are starting to change their view on humans and robots to implement a higher degree of automation, not merely to reduce the pressure on their employees but also to increase productivity. Humans and robots are no longer considered as competitors, but rather as a team with the goal to combine their strengths and advantages. The efficient implementation of human-robot collaboration (HRC) in an assembly process is a way to open up hidden potential [9]-[11]. Robot manufacturers have lately released several robots especially designed to collaborate with humans. These robots are used for producing light objects up to a maximum of 35 kg so that they can be operated without any external sensors [12]. A different concept is the heavy-duty (load 90-300 kg [13]) HRC application, which faces the challenge of avoiding any direct physical contact between the worker and the heavy-duty robot when the robot is in automatic mode. However, physical contact is possible if the robot is directly controlled by the worker using a special control panel. Even if processing from a conventional safety system to a fenceless production enables the combination of the humans and robots strengths, there is still a modest

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amount of implemented HRC applications in industry due to the high innovation grade.

HRC may be one of the most important aspects of future production, but only if it is approached systematically and deliberately. This paper aims to support the assembly planner when considering HRC applications and prevent inefficient and susceptible applications. More specifically this paper provides an iterative guideline, which assists the assembly planner to plan systematically and efficiently by considering the necessary boundary conditions and relevant influence factors, and evaluates the feasibility and profitability in the early planning phases to ensure sustainable success.

II. Human-Robot Cooperation

There are different principles used to create human-robot cooperation. A direct human-robot cooperation, or so-called collaboration, exists if the participants interact directly with one another. The working spaces merge and physical contact is needed [14]. This form of HRC is designed for light robots performing easy and predictable tasks with soft items of low weight. In contrast, this coexistence is an indirect HRC type where the contact between the worker and robot needs to be prevented by keeping a permanent safe distance between them. This type of HRC is about sharing the same workspace. Humans and robots are working at the same time in the same area on different tasks without any physical safety systems.

The idea of using a human-robot-cooperation instead of a robot system with conventional safety systems, such as protective fences, is motivated by the urge to use the existing potential benefits of cooperation between humans and robots. Based on the combination of the strengths and weaknesses of humans and robots, any shortcomings can be eliminated. Fig. 1 summarizes the advantages and disadvantages of humans and robots.

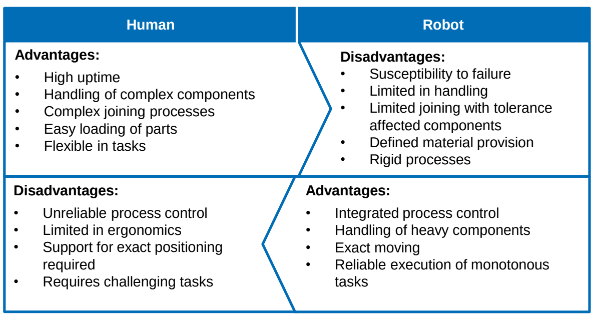

Figure 1. Advantages and disadvantages of humans and robots [15].

An effective HRC application has been designed to assign tasks and processes to the cooperating partners, which fit their abilities and, thus, enable them to pursue the same goal by executing different tasks. One of the main reasons for the low degree of automation in the assembly process is the robot systems' lack of flexibility and insufficient ability to handle complex and limp materials. Monotonous and cyclic processes used for a high quality output are best operated using robots. Further advantages are the handling of heavy components and the use in dangerous environments, such as ergonomically challenging or poisonous work processes. The major disadvantages of using manpower are the limited ability to reproduce highly accurate processes in combination with limited process monitoring. To ensure a high working motivation and, thus, the best results in the long term, humans desire complex and challenging tasks. Humans benefit from processes that require an advanced level of cognitive effort, as well as from processes requiring sensitive abilities, such as the assembly of complex and limp components, e.g. cables.

In combination, humans and robots gain the possibility of constant and reciprocal control, which enables them to detect deviations in quality and technical disruptions at an early stage so that only a small number of products are affected by them.

III. Requirements of a Heavy-duty Human-Robot Cooperation in Automotive Flow Assembly

Automotive assembly is the final division of the production process. Different assemblies and components are joined and deviations from the upstream divisions are compensated, which leads to high complexity. In contrast to HRC applications with stationary objects, this complexity has a large effect on an application in the flow assembly. Other research studies have already defined the different aspects and requirements of a direct HRC in small parts assembly [16]. These results have been modified and extended in this research to match the needs of heavy-duty automotive assembly. Before and during the planning process, these requirements need to be considered and fulfilled by the concept. The identified requirements are structured into three categories, the safety system, ergonomics, and cooperation process/workplace, illustrated in Fig. 2.

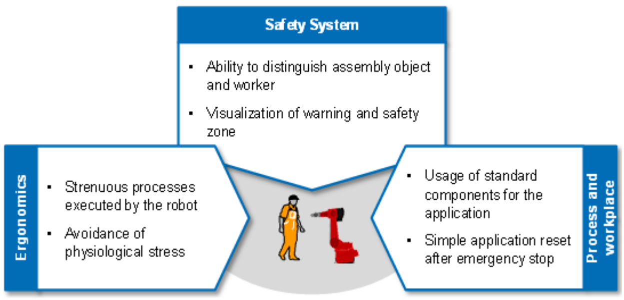

Figure 2. The requirements of a heavy-duty HRC.

The safety requirements are the most critical. The greatest challenge is moving an assembly object, which has to enter the warning and safety zones of the robot. These two zones are designed to protect the worker. If the warning zone is violated, the robot slows down and gives a sign regarding the violation. If the safety zone is violated because the worker or another object has approached the robot too close, it stops immediately [17]. Besides the assembly object, the worker will constantly move near these zones and probably violate them in order to fulfill his tasks. The safety system has to be designed in a manner that enables the system to clearly separate the moving assembly object from any other moving object around the robot. To reduce the probability of an unintended safety zone violation, the limits should be visualized to the worker on the floor.

To increase the ergonomic situation for the worker, it is necessary to release him from hard and strenuous processes, which should be executed by the robot in the future. In the context of an HRC, the ergonomic requirements are not only about the physical strains but also about physiological stress. Working together with a heavy-duty robot can cause the feeling of danger to the worker and this is why the robots operating processes have to be pointed out to the worker.

The requirements regarding the cooperation process and workplace involve economic and efficiency factors. A big issue for HRC applications is the high investment cost due to the fact that they are planned for expensive individual projects without standardization. An implemented application needs to consist of standard components to enable experience and component transfer to comparable conditions. Another technical aspect is the synchronization between the robot and the assembly line. These two components have to be synchronized at all times and be resistant toward oscillation. Because of the open workspace, it is very likely that the safety zone will be accidently violated and the robot will execute an emergency stop. A crash between the robot and the assembly line has to be avoided, in such a case. Besides crash avoidance, the application needs an easy and fast reset procedure to prevent any further production losses.

IV. Planning Approach

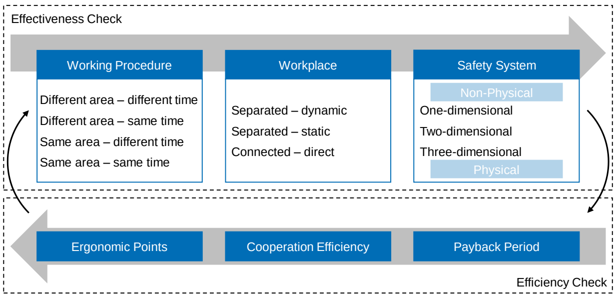

Figure 3. Illustration of the planning approach.

The developed planning approach (Fig. 3) is based on the determined requirements, which are used to identify the different planning modules. As a framework for the approach, a procedure cycle for problem solving [18] was used, which was adapted to the modules and the specific conditions as well as the given case. Divided among the modules in the working procedure, workplace, and safety concept, which cover several organizational and technical elements, each module can be individually used for concept planning. After completing the planning in the modules, an iterative process is started for successful planning. In consideration of the safety concept results, the working procedure and workplace planning are checked, in the so-called effectiveness check, for consistency and adapted if necessary. These processes continue until either the effectiveness is proven or the concept in the result is not feasible under the given conditions.

After the technical and organizational feasibility has been proven, the approach provides a verification scheme based on economics and key process performance indicators to examine the concept efficiency supported by a software interface. Since the approach is based on conceptual planning, it is possible to adapt or cancel the planning without a great deal of effort and high investment costs. The approach can be used to create a variety of concepts, and it allows one to compare them afterwards.

A. *Working Procedure*

Determining the boundary conditions for the HRC application is the first step. Future tasks are analyzed and split into individual sub-elements to decide which of the elements will be executed by the robot and those that will be executed by the workers. Depending on the processes assigned to the robot, the working space is determined. There are three different types of working spaces in an HRC application, the robot area, worker area, and cooperation area, which result from the intersection of both the robot and worker areas. As a result of combining the working areas and the time required by the cooperation partners to execute their tasks, four opportunities for the working procedure are created [19]. A different time and location for the task execution is the most elementary case, which is already very common in industry in the form of physical fences. The transition from an uncoupled time to a process executed at the same time but with different working areas creates a cooperation area due to the very close proximity of the two partners. Dynamic warning and safe zones are required in this case, generating a so-called dynamic cooperation area. Another principle is based on the same working space but accessed at different times. One of the cooperation partners uses the cooperation area, while the other is located in a specific decoupled area, operating independently. For the greatest efficiency, the work process has to be structured in a manner that minimizes the waiting time for access to the cooperation area for both the robot and the worker. The most complex possibility for the working procedure is if the robot and worker are operating in the same area at the same time, resulting in a direct cooperation. A safe cooperation is possible only if the robot has a special control panel permitting the worker to move the robot manually.

B. *Workplace*

The workplace module contains the layout concepts for the application structure underlying the principle of visual declaration of the different work areas. By preventing an accidental violation in the robot area by the worker, the robot can move faster and more efficiently inside its own area. With regards to the worker, this means freedom of movement without having to pay attention to the robot.

Three different workplace concepts were created, which are illustrated in Fig. 4 along with their corresponding organizational working procedures. The workplace had already been divided into two segments by the assembly line. Two of these concepts place the robot on one side and the worker on the other using the existing buffer. Due to the high frequency in flow assembly and the limited availability of space, putting the robot and worker on the same assembly side is an option only if the worker moves the robot manually, otherwise the minimum safety distance may not be ensured.

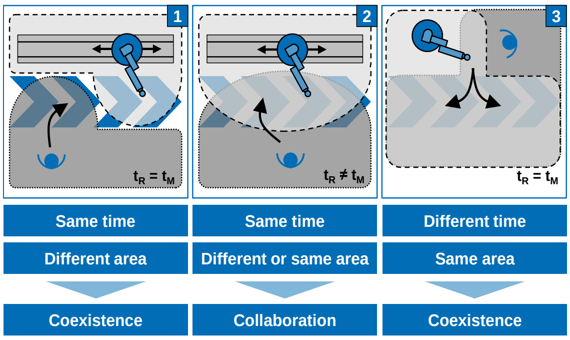

Figure 4. Workplace concepts.

Concept one is for simultaneous operation at different parts of the assembly object and requires a dynamic cooperation area. The robot area is set out in front of the worker to allow him to sequentially enter the working space, which was previously used by the robot. For long cycle times, a linear axle is a conceivable solution for the robot to move parallel to the assembly object [20]. In contrast to the concept where the robot is operating behind the worker, this structure avoids psychological stress caused by the robot and the occurrence of emergency stops if the robot significantly reduces its distance from the worker. This type of workplace requires an assembly object, which is large enough to ensure the necessary minimum safety distance. To increase the space efficiency, the supply materials are located at the sides of the robots and the linear axle is positioned directly behind the robot. In the case of a smaller object, the second concept should be used. Robot and worker enter the cooperation area at different times enabling them to work on the same point of the assembly object. While the worker is operating in the cooperation area, the robot can execute different tasks in automatic mode in its specific area. This concept is particularly suitable in the scenario with a combination of a heavy object and limp parts, such as cables, which have to be joined manually by the worker. The supply materials are again located to the sides of the robot. The third concept should be used if it is not possible to use both sides of the assembly line or to join an object autonomously using the robot. After the robot takes the component for joining in automatic mode, the worker takes control using a joystick [21] and joins the component using the robot as a manipulator. This significantly increases the degree of complexity, which may not be advisable sometimes, depending on the conditions. [22]

C. Safety Concepts

The purpose of the safety concept module is to ensure that no dangers arise for the worker during the assembly process. The first decision that has to be made concerns the safety strategy. There are two different types of safety strategies: Post-collision and pre-collision [23]. Post-collision strategies are designed to tolerate a contact between the robot and human because of the internal robot safety systems. In a heavy-duty HRC, a post-collision strategy will most likely cause serious injury to the human no matter how slow the robot is moving, which implies the safety concept has to be based on a pre-collision strategy. Pre-collision strategies avoid any contact using an external safety system, which consists of non-physical and physical components to keep a minimum distance between the robot and worker.

External safety systems are based a one-, two-, or three-dimensional workspace monitoring system or on a combination of these systems. One-dimensional systems, such as light barriers, are already widespread in industry. These systems are cheap and reliable but they are not appropriate in flow assembly due to their lack of flexibility and should therefore only be used additionally. Two-dimensional systems, such as laser scanners, are able to monitor a level with warning and safety zones. In comparison to one-dimensional systems this has advantages in flexibility but still not with a sufficient degree of effectiveness. Body parts (e.g. outstretched arms) above the level are not detected by the system and therefore have to be added at the minimum safety distance. SafetyEYE developed by Pilz is a three-dimensional secure camera system, which is able to monitor dynamic warning and safety rooms [17], which thereby enables the greatest flexibility. The ability to monitor safety rooms allows it to detect outstretched arms and, thus, reduce the minimum safety distance. By setting up the camera above the assembly station, a maximal area is monitored. The number of dimensions required by an HRC application has to be evaluated individually depending on the specific boundary conditions.

It is essential to calculate the minimum safety distance to evaluate if it fits the planned robot speed and workplace concept. DIN EN ISO 13885 defines a formula that calculates the minimum safety distance depending on the hardware components used and the operating speed of the robot [24]:

$$S = (KT) + C$$

where S is the minimum safety distance, K is the approach speed of the body or parts of the body, T is the stopping time of the system, and C is the violation distance.

In extension to this formula, which is valid for one- and two-dimensional safety zones, the Deutsche Gesetzliche Unfallversicherung e.V. (DGUV) published a modified formula for three-dimensional safety rooms [25]. This modification considers the worst-case scenario in which small objects such as hands are not detected by the system due to a hardware error:

$$S = (KT) + C + S_a$$

where S_a is the tolerance value for the deviations (given by the manufacturer).

Open working areas have the most critical point, where the assembly object enters the warning and safety zones.

Although sensory systems detect unknown objects within their range, it is not possible to distinguish between the assembly object or the worker moving on the assembly line toward the robot. Two alternatives are given to approach this issue [26]: Muting, a temporary deactivation of the sensor system and switching, the protected area is switched when the objects approach. Additionally, it is advisable to use physical safety systems, such as shape macrolon. Other physical systems should only be used if they are compatible with the flexibility and future adaptability. [27]

D. Evaluation

The efficiency check, executed if the feasibility of the system is proven, serves to estimate the usefulness of the created concept or to compare the concepts if several concepts have been created. Therefore, the check, which is based on the principles of cost-benefit analysis, includes three key performance indicators (KPI) that are calculated using a software interface (Fig. 5). The KPIs evaluate the different characteristics of the concept. For the implementation of an HRC application, the most relevant aspects are the economic and ergonomic factors, which have to be gathered due to the fact that they are the only concept information available.

The first KPI was used for economic evaluation. Due to the draft concept, a method is needed, which uses a decision basis with little effort. A method matching this requirement is to calculate the payback period with the net present value method; a dynamic capital budgeting technique. This period can be calculated using the following input:

- Hardware costs
- Yearly employee costs
- Number of employees for a non-HRC concept

To calculate the periodic payback, the number of employees needed for the HRC concept is compared with the number of employees needed for a non-HRC concept. Additionally, it is possible to enter further income or costs for specific periods that may occur. A bar chart is created as the output.

Besides the economic aspects, it is necessary to measure the process efficiency. This is why the cooperation efficiency (CE) is introduced, inspired by the Primary-Secondary-Analysis [28]. The CE represents the time the robot and worker are directly involved in the assembly process:

$$\mathrm{CE} = \frac{\sum_{i=1}^{n} t_{\mathrm{R}i} + \sum_{j=1}^{m} t_{\mathrm{w}j}}{2t_{\mathrm{ct}}}$$

where $t_{\mathrm{R}i}$ is the robot task i, $t_{\mathrm{w}j}$ is the worker task j, and t_{ct} is the cycle time.

A concept without any waiting time is the most efficient one and therefore results in one's CE. If the efficiency is much lower than one, the total waiting time for the robot and worker is calculated and the handling processes are highlighted to identify their potential for optimization. This may be valuable to reduce the robot's handling speed and to shorten the minimum safety distance from the worker in order to raise the CE.

The inputs needed for the CE are:

- The tasks and estimated process time for the robot
- The tasks and estimated process time for the worker
- The cycle time

The KPIs already presented take the economic aspects into account. To complete the evaluation in terms of cost-benefit-analysis, the third KPI aims to evaluate the ergonomics of the concept. A suitable method, based on an absolute scale enabling one to compare different concepts is the ergonomic assessment worksheet (EAWS), which executes a risk assessment of the physical stress to reduce the health risks to the workers [29]. This method is especially suitable because the risk level is expressed in points and classified according to the traffic light principle:

- 0–30 points: Low stress - advisable
- 30–50 points: Increased stress - not advisable
- > 50 points: High stress - avoid

The input required is:

- The ergonomic points according to EAWS

In case the efficiency check was not successful, which means at least one KPI is not satisfactory; the concept modules have to be reviewed to identify their further potential.

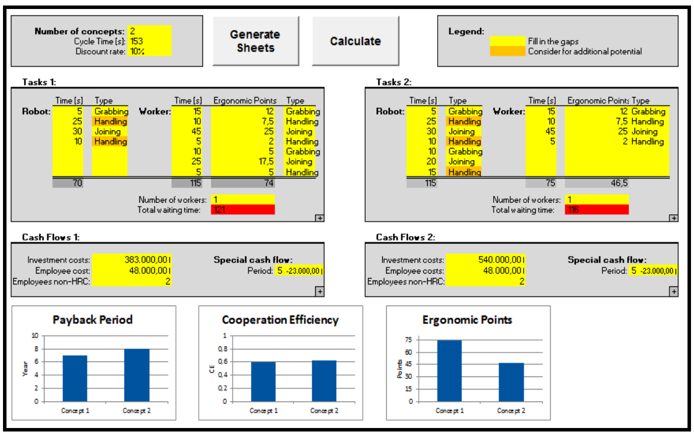

Figure 5. A screenshot of the software interface showing two example concepts.

V. Application of the Approach

In order to validate the use of the approach, it has been applied to a real case in an automotive company. On the basis of an existing assembly station for a heavy object, a concept for an HRC application was created. Several iterations were performed to coordinate the modules with one another to design a safe and high performing HRC application. The development and conception of the modules were carried out in cooperation with various experts in the departments.

An indirect cooperation, the coexistence, was chosen for the working procedure: The same working space at different times. Physically demanding tasks were delegated to the robot, while the worker completes the assembly by joining the limp objects together. The two employees used in the original process could be reduced to one. Therefore, the second workplace concept was selected with the robot and worker on the different sides of the assembly line. Tests showed a direct HRC using a safe robot controller resulted in high pressure and a complex joining process for the worker due to the relatively fast moving assembly object, which did not add any value using the realization of an HRC application. A linear axle was used to increase the robot's available time for the assembly process. The safety system was designed with three-dimensional workspace monitoring system using several SafetyEYE camera systems. Additionally, the access area used for the assembly object was secured with light grids using muting for an approaching object.

As a result, the evaluation showed that the physical pressure on the worker could be lowered and the required workstation space reduced due to the overlapping of the work areas when compared to the original process. Thereby an efficient HRC application is possible, even if the robot is not working at full capacity. Furthermore, the productivity increased because the robots' execution times compared to the former worker times were reduced and thus enabled more assembly tasks to be added to the station to save costs. Besides the increase in productivity and ergonomic aspects, it came apparent that there are still huge challenges regarding the safety of a heavy-duty robot application with non-physical protection. The evaluation revealed that the financial effort necessary to enable a safe HRC cooperation is unjustifiably high. The great variety of sensor technologies required to secure the cooperation area causes investment costs that amortize in the long term. Further iterations led to the conclusion that the reduced costs lead to decreased flexibility and higher safety distances when less tasks could have been executed at the assembly station.

VI. Conclusions

In this paper, an approach for concept planning, a heavy-duty human-robot cooperation in an automotive flow assembly, has been presented. The developed methodology structured the planning process by providing a working procedure and workplace and safety concept modules, which are processed independently and verified using an iteration process. A software interface supports the assembly planner at the evaluation process. The methodology was developed to consider the feasibility of the HRC concepts and is thus not suitable for detailed planning or cost calculations. Process details, such as the precise operation times of the robot or an accurate cost for all the applications elements are considered as secondary considerations.

The practical application of the method pointed several technical shortcomings in HRC technology. The existing technology limits the flexibility too much while causing high investment costs so that the efficiency for some heavy-duty HRC applications may not be ensured. However, the application of the approach verified the practical usefulness of the iterative approach by planning an HRC concept in an existing flow assembly. An assembly planner is able to design solutions to specific modules with different experts by gradual module synchronization and, therefore, able to evaluate the feasibility and efficiency of the concept.

References

[1] W. Diez, "Automotive marketing," Navigation System for New Sales Strategies, Print, Landsberg am Lech: 2006.

[2] H. Becker, "Crash course," Automotive Industry in Global Cut-Throat Competition, Print Berlin: Springer, 2007.

[3] DSW: Datenreport 2014. Soziale und demographische Daten zur Weltbevölkerung: Hannover: DSW, 2014.

[4] S. Krause, "Demographischer Wandel als Herausforderung für Unternehmensführung, Produkte und Märkte am Beispiel der BMW Group," In: Ballwieser, W. (ed.): Demographischer Wandel als unternehmerische Herausforderung. Kongress Dokumentation. 60th German Business Economists' Day 2006. (Series: Schriftenreihe der Schmalenbach-Gesellschaft für Betriebswirtschaft e.V.) Stuttgart: Schäffer Poeschel, S. 3-10, 2007.

[5] M. Schenk and N. Elkmann, "Sichere Mensch-Roboter-Interaktion: Anforderungen, Voraussetzungen, Szenarien und Lösungsansätze," In: Müller, E. (ed.): Demographischer Wandel. Herausforderung für die Arbeits- und Betriebsor- ganisation der Zukunft. Berlin: GITO, S. 109-120, 2012.

[6] S. Kratzsch, *Prozess- und Arbeitsorganisation in Fließmontagesystemen*, (Series: Series of the IMF), Essen: Vulkan, 2000.

[7] A. Zaleski. (2016). Man and machine. [Online]. Available: http://nbr.com/2016/10/31/man-and-machine-the-new-collaborative-workplace-of-the-future/

[8] H. Bley, G. Reinhart, G. Seliger, M. Bernardi, T. Korne, "Appropriate human involve-ment in assembly and disassembly," *CIRP Annals - Manufacturing Technology*, vol. 53, no. 2, pp. 487-509, 2004.

[9] T. Bauernhansl, "Die Vierte Industrielle Revolution - Der Weg in ein wertschaffendes Produktionsparadigma," In: Bauernhansl, T.; ten Hompel, M.; Vogel- Heuser, B. (ed.): Industrie 4.0 in Produktion, Automatisierung und Logistik. Anwendung, Technologien und Migration. Wiesbaden: Springer Vieweg, 2014, S. 5-35

[10] Robert Bosch Manufacturing Solution GmbH: APAS ASSISTANT - Contact-Free Human-Robot-Collaboration, 2017.

[11] K. McCandless, BMW Sees into the Future. (2015). [Online]. Available: https://automotivemanufacturingsolutions.com/technology/seeing-into-the-future

[12] J. Frymann and B. Matthias, "Safety of industrial robots: From conventional to collaborative applications," in P*roc. 7th German Conference on Robotics, 21 - 22 May 2012, International Congress Center Munich (ICM) in Conjunction with AUTOMATI-CA Robotik 2012*, Proceedings for the Conference of ROBOTIK 2012,. Frankfurt am. Main: VDE, 2012, pp. 51-55.

[13] KUKA Roboter GmbH: KUKA Roboter Typenübersicht. [Online]. Available: www.kuka-robo-tics.com/res/sps/a737ee03-5832-4c95-9d91-84e0de80c664_KUKA_Typenuebersicht_de.pdf

[14] S. Thiemermann and J. Spinger, "Direkte mensch-roboter-kooperation," in *ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 96. Jg., 2001, Nr. 11/12, S. 616-620.

[15] S. Thiermann and O. Schulz, Trennung aufgehoben. In: Computer & Automation: Fachmedium der Automatisierungstechnik, 2002, Nr. 8, S. 82–85.

[16] S. Thiemermann, Direkte Mensch-Roboter-Kooperation in der Kleinteilemontage mit einem SCARA-Roboter. Diss. (Reihe: IPA-IAO-Forschung und Praxis, Nr. 411). Heims-heim: Jost-Jetter, 2005.

[17] Pilz GmbH and Co. KG, Sicheres Kamerasystem SafetyEYE. Ostfildern, 2014. Firmenschrift. [Online]. Available: https://www.pilz.com/download/open/Leaflet_SafetyEYE_DE_2014_05_low.pdf

[18] K. Ehrlenspiel, Integrierte Produktentwicklung. Denkabläufe, Methodeneinsatz, Zusammenarbeit. 4. Print München: Hanser, 2009.

[19] E. Helms and C. Meyer, Assistor – Mensch und Roboter rücken zusammen. Einsatz von sicheren und einfach bedienbaren Assistenzrobotern im Produktionsalltag. In: wt Werkstattstechnik online, 95. Jg., 2005, Nr. 9, S. 677-683

[20] J. Werner, Methode zur roboterbasierten förderbandsynchronen Fließmontage am Beispiel der Automobilindustrie. (Reihe: Forschungsberichte IWB, 225). München: Utz, 2009.

[21] ABB Group: Industrieroboter als Produktionsassistenten für die Automobilmontage. Ladenburg, 2008. Pressemitteilung. [Online]. Available: www.abb.de/cawp/seitp202/ecfa3fa16ffe203ac12575010035c522.aspx

[22] B. Sadrfaridpour, H. Saeidi, and Y. Wang, An Integration Framework for Human-Robot Collaborative Assembly in Hybrid Manufacturing Cells, IEEE, 2016.

[23] F. D'Ippolito, F. Alonge, and E. Cucco, "Contact estimation in robot interaction," *Interna-tional Journal of Advanced Robotic Systems*, vol. 11, no. 96, pp. 1-10, 2014.

[24] Norm DIN EN ISO 13855 (Januar 2010): Sicherheit von Maschinen - Anord- nung von Schutzeinrichtungen im Hinblick auf Annäherungsgeschwindigkeiten von Körperteilen.

[25] DGUV Information FB HM-072 (April 2014): 3D-Schutzraum: Anordnung der BWS.

[26] Norm DIN EN ISO 10218 Teil 2 (Juni 2012): Industrieroboter - Sicherheitsanforderungen - Teil 2: Robotersysteme und Integration

[27] A. Vysocky and P. Novak, Human – Robot Collaboration in Industry, TU Ostrava, Czech Republic, MMSJ, 2016.

[28] B. Lotter and H. P. Wiendahl, Montage in der industriellen Produktion. Ein Handbuch für die Praxis. (Series: VDI-Buch). 2. Print Berlin: Springer, 2012

[29] K. Schaub, K. Ghezel-Ahmadi, Vom AAWS zum EAWS. Ein erweitertes Screening-Verfahren für körperliche Belastungen. In: Schäper, M. (ed.): Kompetenz-entwicklung in realen und virtuellen Arbeitssystemen. Bericht zum 53. Kongress der Gesellschaft für Ar-beitswissenschaft vom 28. Februar - 2. März 2007. Dortmund: GfA, 2007, S. 601-604.

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