Procedia CIRP 97 (2020) 423–428

Contents lists available at ScienceDirect

Procedia CIRP

journal homepage: www.elsevier.com/locate/procir

8th CIRP Conference of Assembly Technology and Systems

Concept for an augmented intelligence-based quality assurance of assembly tasks in global value networks

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ARTICLE INFO

Keywords:
Augmented intelligence
Augmented reality
Manual assembly
Assistance system
Industry 4.0
Internet of production
IoP

ABSTRACT

The aim of this paper is to present a conceptual approach to an augmented intelligence-based worker assistance system in manual assembly. This approach is designed to address current challenges in global value networks. We propose a self-learning multi-camera system that (1) provides augmented reality-based assembly instructions and (2) enables automated real-time in-process testing of complex manual assembly operations by using visual camera and CAD data, operational experiences and expert knowledge. As the proposed solution is targeted at enabling SMEs, cost-effectiveness is a main goal of the conceptual approach. Consequently, weak artificial intelligence is applied to realise the algorithmic chain subject to performance restricted hardware. The approach states a novelty in research and development and contributes to practical application in the field of augmented intelligence.

1. Introduction

Industry 4.0, grounded on the integration of key technologies and cyber-physical systems, is expected to profoundly disrupt conventional production approaches (Hellebrandt et al., 2019). These disruptions will affect the organisation of work on both macro (i.e., value networks) and micro (i.e., focal company) level. At the macro level, German companies are increasingly relocating their production facilities abroad in the course of globalisation for competitive reasons and are thus establishing global value networks (Marks, 2019). It is anticipated that the relocation of value creation further increases due to favourable European framework conditions (Lorenzen and Krokowski, 2018) as well as cheaper human labour (Zanker et al., 2013). However, one of the main challenges will be the assurance of high product quality within such global value networks while striving for efficiency optimisation. This challenge is reinforced by the international differences in the qualification levels of employees, especially when comparing high-wage to low-wage countries. According to a study by the OECD, employees from low-wage countries are less educated and with that typically less qualified (Anon, 2019). These qualification differences arise the need for error preventing assembly assistance systems (AAS). To address all levels of qualification, the assembly assistance has to be provided as easy to understand visualisation. A user-centred design assures this understandability (Fischer et al., 2017). On a micro level, various tasks performed by humans are rather difficult to automate in the near future – such as the assembly of tangling parts or tasks of high complexity – for economic and/or technological reasons. Hence, human labour will remain an essential part in future production (Metzmacher et al., 2019). This consideration particularly applies for assembly as a major value-adding process in production (Funk et al., 2018), e.g., in the automotive industry. Assembly is performed manually for complexity or profitability reasons. Through changing market demands, such as shorter product lifecycles, and an individualisation of customer requirements, highly repetitive tasks decline and highly flexible manufacturing systems gain importance. Additionally, technological and market developments will intensify in the next 5 to 10 years. This implies that workers need to be highly flexible to adapt to fast changing

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https://doi.org/10.1016/j.procir.2020.05.262

assembly tasks (Spena et al., 2016). The assurance of this flexibility without decreasing the level of quality requires an automatic adapting, intelligent assistance system. The technique to address this need is artificial intelligence (AI). The constant interaction between human and AI that arises in such a system reveals the need for augmented intelligence models. In this context augmented intelligence is defined as “an intelligent model that requires human interaction” (N-n et al., 2017). The augmented intelligence is an extension of human abilities and incapable of replacing them altogether. That means humans can and will directly influence the input as well as the outcome of the system based of the confidence of judgement of the augmented intelligence (N-n et al., 2017).

Bringing the macro and micro perspective together, following guiding questions can be deduced: (Q1) How can companies assure both a high-level of manual assembly quality and efficiency in global value networks? (Q2) How can low-skilled workers be trained for and guided through highly complex assembly tasks?

As a solution to these questions, we propose a multi-camera system based on augmented intelligence to automatically and adaptively recognise manual assembly steps and create assembly instructions (Q1), cognitive-ergonomically project these assembly instructions with augmented reality (AR) technologies onto work surfaces and parts to guide workers within assembly (Q2) and check against deviations of specified processes (Q1). This is assumed to shorten ramp-up and work preparation time, ensures quality assurance in assembly processes and delivers insights for Design-for-Assembly engineering through the generated data. Consequently, the economic advantage of our research project includes the reduction of quality costs by in-process quality assurance through immediate performance feedback to the workers, reduction of assembly training costs as well as assembly time by guiding assembly instructions. In addition, network synergies will be realised through sharing assembly workflows and data-driven insights.

The remaining paper is organised as follows. Section 2 illustrates the applied research methodology. Subsequently, Section 3 reviews current approaches of and enablers for AASs. Based on existing theoretical as well as practical approaches, Section 4 describes the concept of the proposed solution together with its benefits. Finally, the paper concludes with a discussion of results and formulates implications for future research.

2. Research methodology

Our research process is based on Ulrich (Ulrich, 1982) and can be divided into seven sequential steps (A-G). This paper covers steps A to E. The testing of the proposed solution conducted within steps F and G are not in scope. Following the process of applied sciences, problems with practical relevance have to be identified and structured first (step A). A structured literature review in the field of intelligent assembly assistance as well as emerging trends in the context of globalisation, e.g., flexible value networks (Kagermann et al., 2016), have been the key input for the identification of the underlying practical problems in Section 1. Subsequently, in steps B and C problem-specific theories and approaches of existing research have to be identified, analysed and interpreted. Sections 1 and 3 cover these process steps with a review of current approaches of AASs in theory and practice as well as enablers for AASs. Thereby the problem-specific theories and hypotheses (step B) and problem-specific methods (step C) are considered. Hereinafter, step D is addressed in Section 4 by conceptualising the approach of an intelligent AAS that fulfills the requirements of global value networks. Also covered in Section 4 is step E. This step addresses the detailed elaboration of the approach by developing a practical applicable model. Consecutively, this model has to be validated in practice according to step F. Finally, step G proposes the application of the finalised model in industrial practice. Steps F and G are out of this paper’s scope and will be addressed in future empirical research as outlined in the concluding section.

3. Review of current approaches of and enablers for assembly assistance systems

Current approaches for AASs focus on increasing the quality of the assembly as well as reducing the training times. One approach is to apply AR technologies to guide workers during manual assembly as shown in Alves et al. (2019). Pham and Xiao (2018) developed a workflow recognition system based on object recognition, to automatically extract workflows from manual assembly. This system can be combined with AR-based AASs to enable adaptive responses to the current state of assembly and thus increase the accuracy and scalability of AR solutions. Instead of object recognition (Büttner et al., 2017) used a projection-based AR application and provided it with an intelligent hand tracking algorithm. The tracking of hand gestures enables context-sensitivity. Recognising the hand positions and actions of the worker, the system can draw the users’ attention to wrong picking actions or errors in the assembly process and can adapt the projection to the current working situation.

There are several commercialised solutions (Schlauer Klaus (Optimum GmbH 2020), Assembly Solutions (Assembly Solutions GmbH 2020), Assembly Pro (LAP-Laser 2020), Active Assist (Bosch Rexroth AG 2020)) as well as functioning prototypes from research projects (MonSiKo (Fraunhofer 2020), SWoB (Niedersteiner et al., 2015)) for manual AASs available. These solutions are already well advanced in their maturity. Each of them represents a manual assembly station, which has been equipped with various technologies to provide assembly assistance to workers. As these solutions follow a similar approach, a text-based analysis is not carried out. Fig. 1 shows the analysis of the introduced solutions.

The literature also covers enablers for AASs such as the usability in terms of training, the physical flexibility and the presentation of information within AASs. Oestreich et al. (2019) deal with the impact of digital assistance systems on the initial learning procedure for novice workers. The study shows that novice workers have a similar learning curve with a digital assistance system as with personal explanation. This arises the potential of reducing training costs through digital AASs. Gewohn et al. (2018) examine the presentation of information in AASs in accordance with the needs of the worker. The key insight of this study is that a digital assistance system should be adaptive to the individual’s personal needs depending on the position and tasks as well as problem solving skills. The challenges that come with the design and deployment of interactive worker assistance systems are investigated in Kosch et al. (2017) based on the AAS motionEAP (Funk et al., 2016). They observed that workers experience auditive and haptical assistance as disturbing and only visual assistance as beneficial. Additionally, the system should automatically adapt the amount of assistance the user needs. Quint et al. (2016) present a flexible system architecture for assistance in manual tasks that integrates different assistance modalities. This system proves the feasibility of flexible and cost-effective AASs.

Fig. 1 summarises the main findings of the literature review. For this purpose, we evaluated the reviewed approaches regarding requirements, which we derived and formulated based on the practical problem statement in Sect. 1:

- Flexibility;
- Augmented Intelligence;
- User-centred design;
- Visualisation;

Relevant assembly assistance system solution	Flexibility	Augmented Intelligence	User-centred design	Visualisation	Worker feedback	Optical in-process control	Adaptive progress detection	Automated creation of instructions
Alves et al., 2019	◑	○	○	◕	◔	◕	◑	○
Pham and Xiao, 2018	◔	◔	○	◑	○	○	◔	◑
Büttner et al., 2017	◑	◔	◔	◕	◕	◑	◑	○
Optimum GmbH, 2020	◑	○	○	◑	◑	◕	◑	◔
Assembly Solutions, 2020	◑	○	◔	◕	◑	◕	◔	◕
LAP-Laser, 2020	◔	○	○	◕	◑	◔	●	○
Bosch Rexroth AG, 2020	◑	○	○	◕	◑	◕	◔	○
Fraunhofer IPA, 2020	◑	○	◔	◑	◔	◑	◔	○
Niedersteiner et al., 2015	◑	○	○	◑	◔	◕	◔	○
Oestreich et al., 2019	◕	○	◔	◕	○	○	◔	○
Gewohn et al., 2018	◕	○	○	◕	◕	◑	◕	◔
Kosch et al., 2017	◔	○	◕	●	●	●	●	○
Quint et al., 2016	●	○	○	●	◕	●	◑	○

○ *Requirement not met* ● *Requirement completely met*

Fig. 1. Comparison of current approaches of and enablers for AASs.

- Worker feedback;
- Optical in-process control;
- Adaptive progress detection;
- Automated creation of digital assembly instructions;

Flexibility is a necessary requirement to quickly adapt an AAS to changes in complex market environments (e.g. global relocation of production facilities) and shorter innovation cycles (Spena et al., 2016). AI algorithms are a fitting tool to enable this flexibility. But since human labour remains an essential factor in productions of the near future, those AI algorithms have to allow the workers to intervene and overrule them (Metzmacher et al., 2019). Thus, augmented intelligence systems have to be developed (N-n et al., 2017). Since humans use the system, the acceptance of this system is an important factor for a successful implementation in existing production systems. A user-centred design can be beneficial to achieve this acceptance (Fischer et al., 2017). Further, Kosch et al. (2017) explain that visual assistance is the only beneficial form of assembly assistance. That makes visualisation a crucial requirement for an effective AAS. In-process quality assurance can be achieved through real-time worker feedback, as errors during the assembly process can be eliminated or prevented immediately. This reduces the quality costs significantly (Tönnes et al., 2016). The requirements for real-time worker feedback are optical in-process control and adaptive progress detection (Pham and Xiao, 2018; Büttner et al., 2017). Furthermore, an automated creation of assembly instructions reduces the ramp-up time as well as the personnel costs as no human interaction is needed. Additionally, the overall quality level constantly improves through automated optimisation of the assembly instructions.

Taking into account the analysis of the described approaches and enablers (Fig. 1), current research considers AR as a suitable tool to assist workers in manual assembly. AR can be used in order to adapt faster to changing demands in assembly procedures, improve assembly time as wells as lower failures during the assembly process. Additionally, several authors (see Funk et al. (2019) or Gewohn et al. (2018)) highlight the potential usage for an in-process quality assurance during the manual assembly process. The combination of these applications with AI to create augmented intelligence solutions and therefore highly flexible systems, was only examined in the case of context recognition by Pham and Xiao (2018) and Büttner et al. (2017). None of the approaches used a combination of object and hand gesture recognition, which would be beneficial for the accuracy of the context recognition (Pham and Xiao, 2018). Consequently, there is no approach for an intelligent AAS, which can automatically generate assembly instructions and assure in-process quality. Furthermore, the focus in current approaches to manual AASs was rather technical. A user-centred design was not explicitly considered and the acceptance of these AASs by the users not specifically regarded (Fischer et al., 2017).

Finally, challenges in context of global relocation, like intercultural aspects and location-independent use, are not addressed in any of the current solutions. The applications do not enable an integration into flexible global value networks (Kagermann et al., 2016). To overcome those challenges, an AAS has to allow location-interdependent in-process quality assurance. It has to adjust assembly instructions automatically to different user needs, depending on the corresponding cultural circumstances, by processing user feedback in real time.

4. Concept

4.1. Setup characteristics

In order to meet the flexibility requirement, the proposed system (Fig. 2) will be developed in a modular approach. It consists of a software and hardware module, which can be adapted to the respective application and further developed independently of each other. Different applications are for example automotive or switchboard assembly, which differ in size and complexity of the assembled parts.

4.1.1. Hardware module

The hardware module allows to create the assembly instructions at the development sites of a company. The preparation of cognitive-ergonomic assembly instructions is based on expert assembly and fully automated. To achieve this, hardware is required that can capture the necessary data of an expert assembly (visual data) and has the necessary interfaces to the CAD programs in use. Additionally, the same setup can be implemented in the assembly lines to guide the assembly workers and assure real-time in-process quality. To capture the necessary visual data, the hardware module consists of five cameras (3 x Raspberry Pi Camera Module v2; 2 x Longrunner Wide Angle 160°Fisheye Lens). Microcontrollers (Raspberry Pi 3B) control the cameras and send the data to a central computer, which processes them. A projector controlled by the central computer provides assembly instructions. The camera

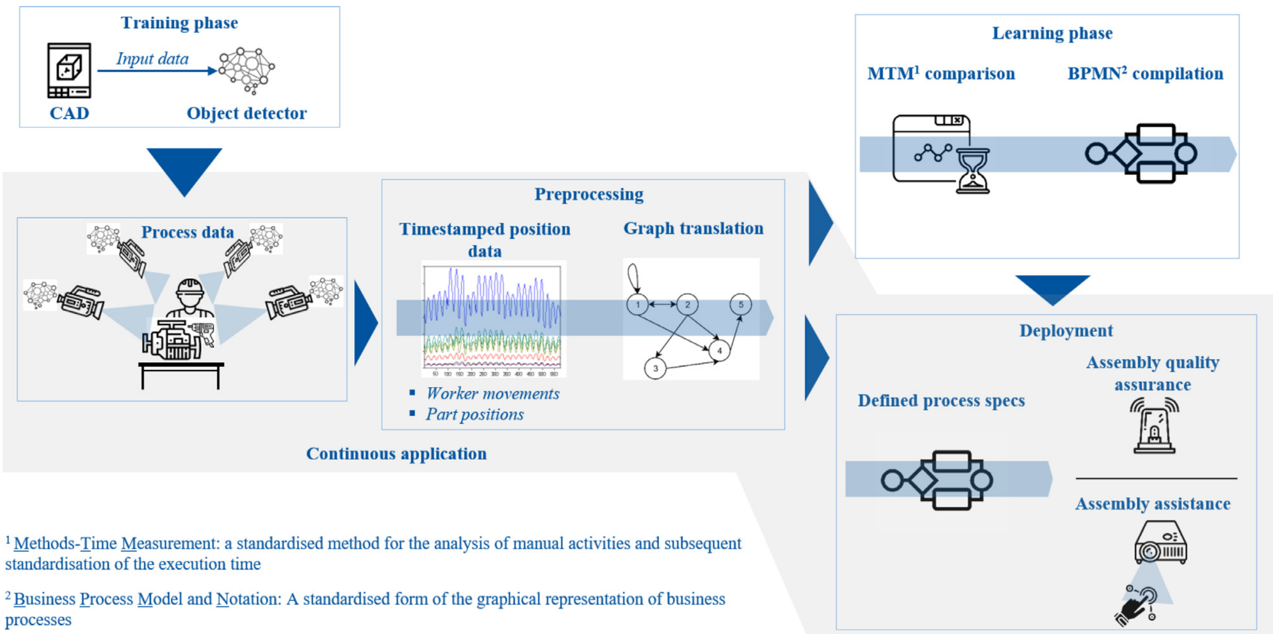

Fig. 2. Description model of the proposed concept.

system works as the receiving part of the human machine interface as it captures the necessary information to adapt to the environment, whereas the projector is the communicating part, which presents information to the user. When selecting hardware, cost-effectiveness is of high relevance, so that the system is feasible for small and medium sized enterprises (SME). This enables SMEs to take part in the trend of globalisation (Kagermann et al., 2016).

4.1.2. Software module

The software module is the centre of the proposed system and incorporates the necessary AI algorithms for the system to work. Those algorithms ensure the workflow as well as three-dimensional parts recognition and generate cognitive-ergonomic, AR assembly instructions. This guidance will be automatically adjusted to the user's needs to broaden his or her skillset.

4.2. Approach

The proposed technological implementation of the hardware module is a multi-camera system (Fig. 2). The concept is designed like an assembly workstation and equipped with optical image acquisition systems (cameras) and a projector. Placed directly in the development department, it is used to train the AI (training phase) with expert assembly of new parts to generate process data. Then the AI algorithms can process the captured visual timestamped position data (worker movements and part positions) together with available CAD data and create AR-based assembly instructions through graph translation.

Implemented in the operative assembly process, the camera system is capable of recognising the parts used and the assembly steps executed three-dimensionally. Together with the underlying information about the assembly process, generated through CAD data and expert assembly, the software module generates the situation-based cognitive-ergonomic assembly instructions and ensures in-process quality through real-time assembly progress evaluation. To prevent assembly errors, workers are provided with AR assembly instructions and receive real-time visual feedback on the quality of their assembly progress. The instructions will be projected on the work surface and/or the product itself. This way the assembly worker stays free from wearables. Based on the problems that occur during the assembly of a product, the software module will automatically optimise the assembly instructions (learning phase) with the help of MTM comparison and BPMN compilation (see Fig. 2). Thus, augmented intelligence algorithms improve overall process and product quality. The augmented intelligence system reduces the time necessary for assembly training by providing detailed situation-based assembly instructions of new products and thus guides the assembly worker through new processes.

With respect to the technical development of the multi-camera system, following aspects play an important role in the software module: (1) Image recognition and machine vision, (2) state estimation of tracked objects and (3) clustering and comparison algorithm. Additionally, (4) the use of performance restricted and low-cost hardware. With regard to (1), many weak AI algorithms of the machine learning domain can be facilitated, such as YOLO V3 Network to detect parts and workers (Redmon et al., 2016). For state estimation (2), common algorithms like solvePNP can be used to estimate 3D positions via multiple camera perspectives and the previously detected objects of interest (Lee et al., 2018). With the timestamped data, clustering algorithms (3) such as DBSCAN (Ester et al., 1996) are used to define prominent movements. With the help of process mining algorithms, those sequences of prominent movements are translated into a graph structure. From here on, the data can be either compared to predefined processes to detect deviations for quality assurance or used to deduce the succeeding assembly step to guide workers via AR-projected assembly instructions. The corresponding technological research gap lies within the robustness, applicability and combination of existing algorithms with respect to performance-restricted hardware.

4.3. Outcome

The novel approach of a self-learning multi-camera system for representation of the assembly process and subsequent generation of assembly instructions uses state of the art in weak AI (i.e., machine learning algorithms). This replaces the need for manually recording and mapping process steps and cycle times during work planning. Moreover, the system is capable of providing assembly instructions with AR projection and enables automated real-time in-process quality assurance. Current approaches rely on predefined assembly instructions, based on CAD data. The expected technological outcome is new as the system automatically generates assembly instructions. Those instructions are based on camera and CAD data as well as operational experiences and expert knowledge. They will be automatically improved throughout the whole product life cycle. Furthermore, applying process-mining approaches to physical processes states a novelty in terms of research and development.

60% of the total quality costs originate from manual assembly processes. These costs consist of failure costs, failure prevention costs and testing costs (Tönnes et al., 2016). With the help of real-time AR assembly instructions and automated in-process quality control, the developed system is able to ensure high quality and efficient assembly operations in global value networks. On the one hand, training for assembly processes can easily be shared and reproduced with the system in a global value network. On the other hand, AR assembly instructions reduce the qualification requirements of the assembly workers and thus enable the integration of low-skilled workers for the assembly of complex parts. This allows company locations in global value networks to focus on their core competencies to increase efficiency and remain competitive. Application of AI ensures the continuous improvement of the assembly processes and thus of the overall quality. In addition, time for the creation of assembly instructions can be decreased through automating this process with the help of AI. The proposed system will therefore reduce quality costs in all three areas (Niedersteiner et al., 2015; Falck et al., 2010).

5. Discussion and future research

The developed concept states a novelty in research and development as it uses weak AI to create a highly flexible and adaptive AAS. It represents a possible solution for the identified challenges of globalisation. The research questions raised can be answered in theory, as the system can take over in-process quality assurance (Q1) and reduces training and ramp-up times (Q2). Due to the user-centred design combined with AI, the developed AAS can adapt itself to the needs and qualification level of the user allowing location-independent and intercultural use. Thereby the system meets the requirements for an integration into global value networks and enables the relocation of assembly plants into low-wage countries.

The developed model is based on recent literature and the latest state of the art. The studies on which the concept is based show a consensus in the use of visual aids for manual assembly activities. Context-sensitive assistance, based on the work steps performed, is also repeatedly listed as necessary and beneficial. Based on previous work, it can be concluded that the above-mentioned AI algorithms are capable of performing the operations for creating assembly instructions and context-sensitive assembly assistance using AR.

Nevertheless, the proposed concept is a complex theoretical model, the functionality of which has not been tested and therefore not been proven. The complex interrelationships between the individual components of this system (such as the different AI algorithms) offer a wide scope for errors and difficulties. A purely theoretical model cannot adequately capture those flaws. Additionally, it has not yet been sufficiently considered what cognitive ergonomics and a user-centred design means in the context of manual assembly.

In future research, the following steps have to be taken in order for the presented concept to achieve its intended benefits. A first prototype consisting of the presented modules has to be developed and its basic functionality ensured in practice. The prototype has to allow automatic in-line process control as well as a creation of digital assembly instructions. Furthermore, it has to be studied which features are inherent to a user-centred design of a manual AAS and the fundamental aspects of cognitive-ergonomic AR assembly guidance have to be examined. This analysis should also cover cultural differences and language issues in global value networks. Regarding the managerial aspects, organisational processes for sharing the assistance system data in a global value network have to be developed. Finally, it has to be investigated how the collected data can be anonymised in order to guarantee personal and data security. Although the concept is a theoretical model, the highlighted potentials justify further research activities as well as a prototypical implementation.

Acknowledgements

The research project was carried out in the framework of the industrial collective research programme (IGF/CORNET no. 273 EN). It was supported by the Federal Ministry for Economic Affairs and Energy (BMWi) through the AiF (German Federation of Industrial Research Associations eV) based on a decision taken by the German Bundestag.

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