Human-Centered Design of Hybrid Cyber-Physical Production Systems

Use of Human Autonomy Teaming as a Future Way of Working

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1. Motivation

Many production processes are changing toward hybrid cyber-physical production systems (CPPS) in which physical and computational elements and humans are interconnected (Spath et al., 2013). In such hybrid CPPS, humans work together with intelligent and automated or autonomously acting systems (hereafter in this section collectively referred to as automated systems). The allocation of tasks to automated systems enables economic advantages through more efficient processes, error reduction, quality improvements, or easier work for operators. Consequently, it contributes to sustainable production, preserving resources (e.g., by reducing waste or saving energy due to error prevention and increased efficiency). Besides, it positively impacts operators (e.g., by eliminating physically demanding tasks or by reducing cognitive workload through assistance systems) (Chen et al., 2020; Santochi & Failli, 2013).

An important design question of automated systems is the distribution of tasks among the different actors. With respect to the type and extent of the automated tasks compared to human work tasks there are different approaches of system design (Parasuraman et al., 2000), e.g., allocation of tasks according to feasibility and costs (Manzey, 2012; Salvendy, 2012). Beyond these rather technical and economical motivated approaches, other ideas consider humans and automation as a complementary, hybrid system in which humans take the role of supervisory control (Sheridan, 2012) or operate as partners (O'Neill et al., 2020). Here, various design guidance is available such as the creation of active involvement of people, access to complete and real-time information on automated tasks to create adequate situational awareness (Endsley, 1995), and the consideration of both operators and automation as equal and independent actors of the overall system (Manzey, 2012; Sheridan, 2012). Additionally, further research work considers the role of humans in CPPS in general as that of a partner of automation, which takes a central role in a partially automated, human-centered production system (Operator 4.0) (Rauch et al., 2019; Romero et al., 2016).

But how do these different approaches and principles of designing hybrid CPPS affect the overall system performance and, in particular, the operators in detail? The knowledge of these effects is of significant importance for the usability of

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these concepts (Rauch et al., 2019) and will be crucial for their success. Therefore, this paper deals with how these systems must be designed to achieve both economic and human-centered goals (e.g., overall system performance, work performance, workload, human work perception, or sustainability). We first present the results of a first literature review on the state of the art regarding the interaction of humans and autonomous systems in production systems and the associated division of work (Human Autonomy Teaming, HAT). Here, we especially emphasize autonomously acting systems. On this basis, open questions regarding system design are derived (e.g., in terms of degree of autonomy or interface design). Finally, we propose and discuss preliminary ideas and starting points to solve these design issues. These shall serve as a basis for future research work.

2. Human Operators in CPPS

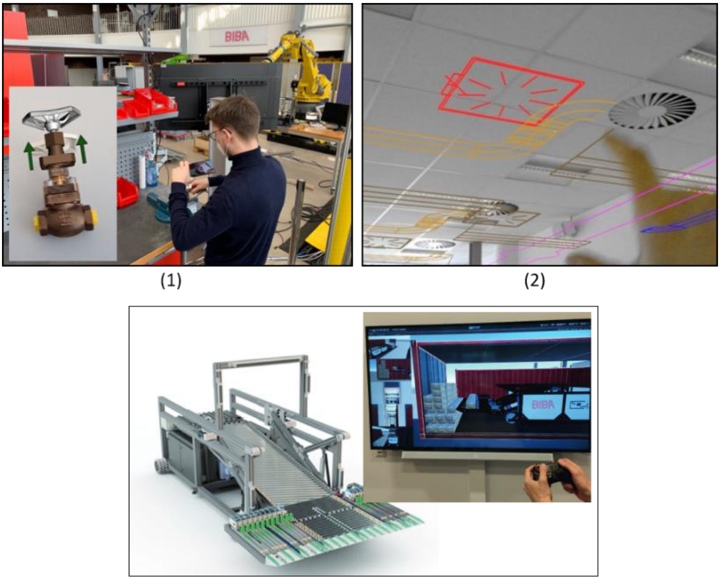
Work design addresses measures that contribute to a change in existing work systems or the creation of new ones. A work system consists of humans, workplace, work equipment, work environment, and work organization (Spath et al., 2012). From a human-centered perspective, work design is concerned with creating work systems that enable safe work that is neither physically nor mentally exhausting (Wegge et al., 2014). Hackman and Oldham (1976) have described various motivational effects for operators in this context, e.g., through task variety, comprehensiveness, and meaning (Oldham et al., 1976), which continue to be an essential basis of work design nowadays. Autonomy in execution and feedback on the task outcome were also identified as beneficial (Hackman & Oldham, 1976).

Implementing CPPS will bring profound changes within work systems in many manufacturing work domains (see Section 1) and thus put the applicability of existing principles in the focus of research. A human-centered design of the new work plays a crucial role in determining the extent to which targeted quality or performance improvements are achievable. A central challenge here is the design of interfaces between operators and machines. Only if operators working with and on the CPPS can control and comprehensively understand its actions, adequate decisions in line with the CPPS are possible (Hirsch-Kreinsen, 2014). In Stern (2020), based on a study-based investigation with 68 participants, the authors showed that different design elements of work in CPPS (e.g., level of information display and type of user interface design) have significant effects on work performance and work perception (Stern, 2020).

Although the ideas regarding CPPS based on Industry 4.0 concepts have not yet been finalized or fully established, we are already starting to look at the subsequent Industry 5.0 (Nahavandi, 2019). Industry 5.0 focuses on the interaction between humans and autonomous systems, while Industry 4.0 is primarily based (only) on interconnected, automated systems. In Industry 5.0, humans and machines act together to bring human capabilities (such as creativity or cognitive skills) to fruition through the collaborative support of machines while liberating humans from tedious, repetitive tasks (Nahavandi, 2019). In this way, efficient and value-added production is possible, which can also be resource-efficient (e.g., in terms of material waste or energy consumption during production). Industry 5.0 can thus contribute to current sustainability and environmental goals (Nahavandi, 2019).

In summary, the concept of Industry 5.0 is based on intelligent assistance systems and tools, and intelligent automation or autonomous systems that enable collaboration between humans and machines. In this context, trust and reliability are decisive criteria. As a result, significant increases in efficiency are possible, including error-free production (Nahavandi, 2019).

Linked to considerations on Industry 5.0, there are also already initial characterizations of the role of people within these systems. Operator 5.0 describes a human operator in production systems who interacts with machines (in this case, robots, automated and intelligent systems) in a trusting manner and utilizes the potential of CPPS (Romero & Stahre, 2021). The authors assume that this will result in levels of efficiency, productivity, and resilience of CPPS that neither fully automated nor classic manual systems can achieve (Romero & Stahre, 2021). Such systems can be, for example, the interaction of humans with intelligent cognitive assistance systems or collaborative robots. Figure 1 depicts examples of such systems: (1, 2) show cognitive assistance systems based on a smartphone (1) and data glasses (2), which display context-dependent Augmented Reality (AR) virtualizations for assembly and maintenance support based on image recognition methods (Quandt et al., 2020; Stern et al., 2021). (3) shows a collaborative robot system that supports the unloading process of containers by autonomously performing unloading operations under human supervision (Petzoldt et al., 2020; Rolfs et al., 2020).



(1) (2)

(3)

Figure 1: (1) cognitive AR assistance system (smartphone), (2) cognitive AR assistance system (data glasses), (3) interactive robot unloading system

Involving operators in the design of CPPS can be done by applying Human-Centered Design (HCD) approaches, which provide for an intensive alignment of the development process with the users' requirements (Boy, 2011). One example of HCD is Contextual Design, a method that considers the context and the requirements of a system to be developed. Here, requirements are elicited via interviews, the obtained information is consolidated and analyzed, and an idea is derived. The idea again is evaluated with users at the prototype level. The approach emphasizes the importance of a clear picture of user requirements, which designers cannot replicate independently. For this purpose, user input is required (Holtzblatt, 2009; Jacko, 2012).

In summary, the change of production systems towards CPPS according to the Industry 4.0 and, in particular, the Industry 5.0 concepts evoke new forms of cooperation between humans and machines. In Stern (2020), the authors could show the effectiveness and positive effect of HCD on work performance and work perception for CPPS for a collaboration of humans and (partially) automated systems (Stern, 2020). Going further, it now seems necessary to adapt and transfer previous findings for a human-centered work design to CPPS according to the Industry 5.0 concept, i.e., in the sense of collaboration between humans and autonomous systems as HAT.

3. Human-Autonomy Teaming in Manufacturing and Logistics

The implementation of CPPS often requires intelligent and autonomously acting systems (Schelble et al., 2020). Examples of this are predictive maintenance, cognitive assistance systems, or collaborative robots based on artificial intelligence (O'Neill et al., 2020). In the case of interaction between humans and machines, this is referred to as HAT (Demir et al., 2019; Schelble et al., 2020).

HAT describes an interaction between (multiple) humans and (multiple) autonomous systems with mutual dependencies regarding work actions and the achieved work results. All team members (both humans and machines) have clear roles and pursue a common goal in completing the task (Demir et al., 2019; O'Neill et al., 2020). A distinction is made between the concepts of automation and autonomous systems. Automation is the execution of a task by a machine that was previously fully or partially executed by humans (McNeese et al., 2018; Parasuraman et al., 2000). The degree of this task takeover (automation level) was described by Parasuraman (2000) by the level of automation (LOA) continuum. It ranges from fully manual tasks to low and medium LOA, where basic tasks are performed by the machine, to full automation, where the machine alone decides and executes. At the same time, the human operator has a passive role (Endsley, 2017; O'Neill et al., 2020).

According to Parasuraman (2020), O'Neill et. al (2020) made a transfer to autonomous systems as an adaptation of the LOA continuum. Here, the original LOA was transferred into three groups of autonomous systems (no autonomy, partial autonomy, and high autonomy). Figure 2 shows this continuum. According to O'Neill et al. (2020), for a human-machine-system to be designated according to the concept of HAT, there should be at least partial autonomy (corresponding here to level 5 on the original LOA continuum, where the machine performs a spontaneous action after confirmation by the human operator) (O'Neill et al., 2020).

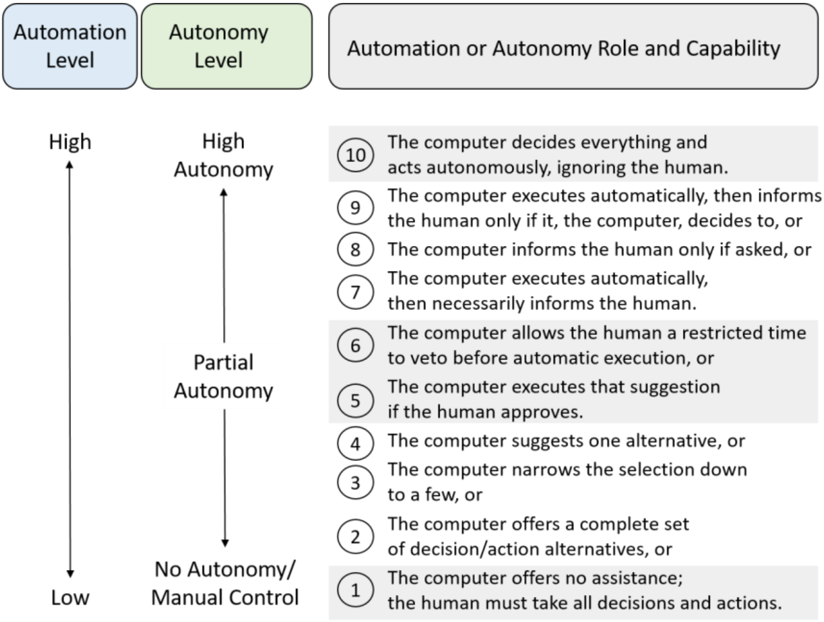


Figure 2: LOA continuum for autonomous systems according to O'Neill (2020) and Parasuraman (2000)

The concept of HAT has many overlaps not only with the ideas of Industry 5.0 (4.0). Still, it can also be found within the ideas of Smart Factory or Smart Production, Ubiquitous Manufacturing, and Digital Manufacturing (Mabkhot et al., 2018). For example, the role of humans is also discussed in the Smart Factory and described as that of a highly skilled operator who is not only involved in the manufacturing process in a traditional way but is also responsible for monitoring and supporting the autonomous systems (Mabkhot et al., 2018).

Overall, the interface between humans and machines is addressed in many research works investigating use cases within CPPS, even without an explicit focus on HAT (Stern 2020). For example, (Mabkhot et al., 2018) describes an assembly work system in which necessary tools, work steps, and the complete CAD model of the product can be visualized. In addition to classic displays or handhelds, projection or AR can also be used as hardware (Mabkhot et al., 2018). The human-machine interface design in CPPS is as a crucial challenge (Hirsch-Kreinsen, 2014; Siepmann & Graef, 2016).

Furthermore, a human-oriented work design in CPPS also leads to sustainable production systems. Besides its beneficial impact of resource consumption and energy usage mentioned in Section 1, sustainable production can also be achieved through sustainable work in terms of physical and mental health, satisfaction, working conditions, or opportunities for learning and training (Santochi & Failli, 2013). This requires minimizing employee stress through knowledge and involvement, trust, and ergonomics (social, mental, and physical). Sustainable work can be achieved, for example, by providing information in the direction of the operator (e.g., about products, processes, and scheduling) and in the direction of the autonomous system (e.g., about difficulties, errors, suggestions) (Santochi & Failli, 2013).

In summary, a central role of humans in the production systems of the future is postulated by many sources. In a paper by Zhou et al. (2019), the term Human Cyber-Physical System (HCPS) is used for this purpose. It refers to an intelligent production system that consists of humans and digital and physical systems with the aim of achieving production goals in an optimized way (Zhou et al., 2019). Here, the CPPS are based on intelligent, autonomous systems (Gronau, 2016; O’Neill et al., 2020; Schelble et al., 2020).

4. Design Issues for Applied Human Autonomy Teaming in CPPS

To answer design questions around HAT in CPPS, we first look at existing findings from other application areas. In an extensive systematic literature review, O'Neill et al. (2020) examined existing research on HAT. Due to their comprehensive and systematic approach, this publication is used as the central and main source for a depiction of the current state of the art regarding HAT in this work. The authors evaluated 76 papers on this topic, which included studies that addressed HAT in the sense of collaborative task completion, i.e., that involved teams consisting of humans and machines. The machines acted at least partially autonomously. The studies examined were thereby categorized by the authors into their input factors (1), which go through mediators (2) and ultimately lead to outputs (3). Thus, within the studies, various independent variables were used as input factors (such as task type, task difficulty, team composition, and degree of autonomy) and led to effects to be studied on various dependent variables as outputs (such as performance, confidence, situational awareness) (O’Neill et al., 2020). Mediator factors, such as communication, have been examined in only a few studies. Figure 3 provides an overview of the inputs, mediators, and outputs studied.

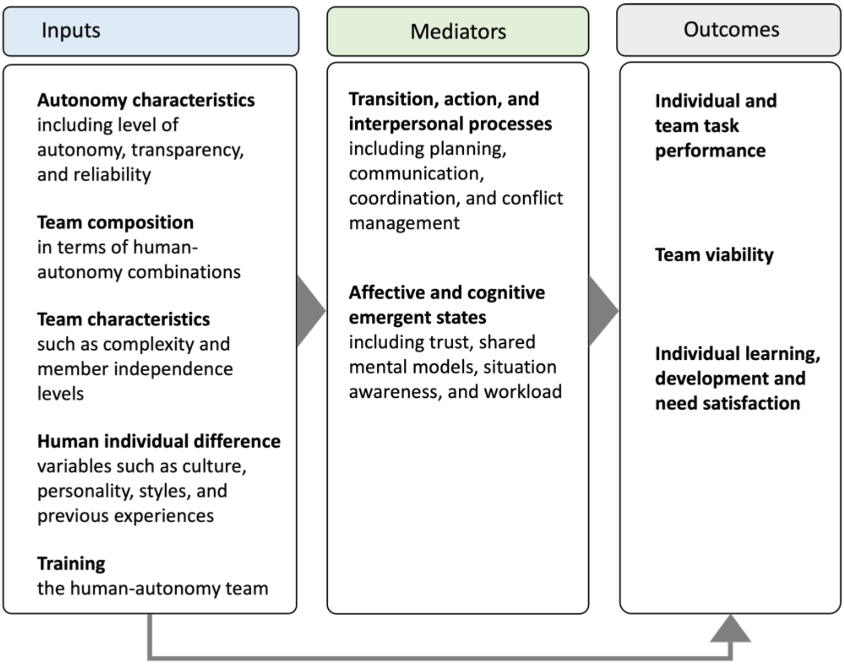


Figure 3: Inputs, mediators, and outputs studied in HAT performance research examined by O'Neill et al. (2020)

The authors were able to draw the following conclusions (among others) during the evaluation and derive open research questions (O'Neill 2020):

Level of autonomy: Overall, a high level of autonomy has a predominantly positive effect on employees and task completion. Regularly, this is also accompanied by higher development costs. However, the available studies have not been conducted under field conditions but only under laboratory conditions (O'Neill et al., 2020). This leads to the following open research question: When is which level of autonomy beneficial, e.g., depending on specific task types?

HAT system performance: in existing studies, a HAT was generally inferior to a human-human team in terms of work performance. However, there is a need to identify the mechanisms that act on the system performance of a HAT. The authors expect that with knowledge of these mechanisms, underlying potentials can be unlocked (O'Neill et al., 2020).

Agent interdependence: Studies indicate that interdependence among agents within a HAT is beneficial to achieving good system performance (O'Neill et al., 2020).

HAT for complex work tasks: The theoretical expectation that HAT, or the use of autonomous systems, leads to superior system performance for particularly complex work tasks could not be confirmed (O'Neill et al., 2020). The authors suggest at this point that the autonomous systems were not sufficiently well designed for the tasks they were given. In principle, complex tasks should be performed by autonomous systems to reduce human workload (O'Neill et al., 2020).

Communication in HAT: Communication between humans and machines within HAT should be organized differently from that between humans. In HAT, (relevant) information should be given to humans in the right way (push principle) instead of offering it only on demand by humans, as this creates delays (pull principle) (O'Neill et al., 2020). There is a need to find out what is the impact of the form of communication used and the way information is shared, e.g., in terms of transparency, reliability, the form of communication, or level of information (O'Neill et al., 2020).

Effect mechanisms of HAT: Many of the studies examined refer to typical input factors and outputs but neglect the effect mechanism that takes place in between. For example, out of the studies reviewed only communication between actors within a HAT was examined but no other mediators, such as how teams coordinate within the HAT. Moreover, mediator factors were often treated as outputs (O'Neill et al., 2020).

Training for HAT: The training of actors within HAT is seen as a significant influencing factor. Since the collaboration with autonomous systems is new to many operators, a steep learning curve can be assumed. This should be taken into account in studies. Furthermore, the training itself, e.g., the choice of the correct form of training for HAT, should also be the subject of research (Demir et al., 2019; O'Neill et al., 2020).

Long-term effects of HAT: There have been no long-term surveys of HATs (longitudinal studies) up to now. Therefore, no conclusions can currently be drawn about the development of the system performance of HAT over time (cf. also Training for HAT) (O'Neill et al., 2020).

Human-centered design of HAT: Autonomous systems must be designed for use as actors within a HAT. This design differs from the general design of an autonomous system, as interaction with humans poses special requirements. This is reflected, for example, in the poor performance of HAT compared to purely human teams. If the autonomous systems are to take over a role that has so far been assigned to humans, improvable system performance is to be expected. Instead, such a role should already be considered at the early stages of the development process and be suitable for an autonomous system's requirements. Future research should thus jointly address the needs posed by the work task, the associated role, and the appropriate design of autonomous systems (O'Neill et al., 2020). This includes the question of how autonomous systems are designed in terms of their technological basis (Demir et al., 2019).

The authors conclude by pointing out that HAT is very likely to be a relevant form of work in the future. Therefore, primary research around this area is of particular importance (O'Neill et al., 2020). As a first step towards a solution to these open research questions, Schelble et al. (2020) worked on deriving a framework for the design of autonomous systems within HAT for CPPS based on application-oriented studies. The framework is intended to enable users to make informed decisions about the development and integration of autonomous systems within Industry 4.0 applications leading to better, more efficient, and customized HAT. Figure 4 shows their framework.

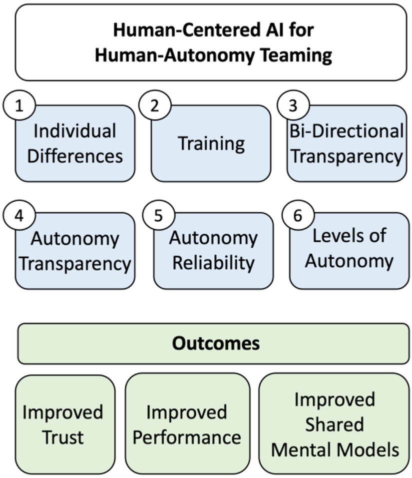


Figure 4: Framework on design factors for HAT in applied settings of CPPS and their outcomes (according to Schelble et al. 2021).

The factors of the framework are intended to be interpreted in the order of individual differences, training, bi-directional transparency, autonomy transparency, autonomy reliability, and levels of autonomy. They can help achieve outcomes in the form of improved trust, improved system performance, and improved shared mental models. Table 1 provides an overview of the content and design recommendations related to each factor (Schelble et al., 2020). The framework provides an essential and helpful basis for the development of autonomous systems for use within HAT.

Factor	**Content**	**Design Recommendations**
Individual Differences	Operators have different characteristics, e.g., due to culture, background, or life experiences.	Conduct user studies prior to developing and implementing a HAT to determine the existing characteristics in the current workforce so that a suitable system can then be developed.
Training	Training operators and autonomous systems to work together leads to better system performance.	Conduct training and familiarization activities for operators with autonomous systems to create transparency about how they work.
Bi-Directional Transparency	Both the employees and the autonomous system should be transparent to the other agent to enable adaptive collaboration.	Development of the HAT using appropriate interfaces that generate transparency for the operator and use of sensors, e.g., about the physiological state of the human that generates transparency for the autonomous system.
Autonomy Transparency	Knowledge of the operator about the autonomous system, including capabilities, intention, decision making, and state.	Generation of knowledge through training. Finding an appropriate level of information to convey relevant information but avoid information overload.
Autonomy Reliability	The reliability level of the autonomous system directly affects the system's performance.	The goal in developing the autonomous system should be to optimize reliability (>70 percent). Additionally, combined with training and transparency, a positive effect on system performance can be achieved even with lower reliability.
Levels of Autonomy	The Level of Autonomy describes the distribution of tasks and competencies within the HAT (1-10, 1: manual system, 10: fully autonomous system).	The choice of the Level of Autonomy is of crucial importance in the development of the autonomous system/design of the HAT. In particular, it should be ensured that adequate situational awareness is maintained for the human, i.e., the human remains in the loop, thus avoiding errors.

Table 1: Contents and design recommendations regarding the framework's on HAT design factors (according to Schelble et al., 2020)

In line with the authors' conclusions, both at (O’Neill et al., 2020) and (Schelble et al., 2020), we agree on the need of further research on the open research questions as pointed out and on a further detailing of the framework. Consequently, this could improve its usability for different use cases (e.g., work areas in manufacturing and logistics, use of purely cognitive or (also) physical autonomous systems).

5. Towards Design Guidance for Applied Human Autonomy Teaming in CPPS

Outside of CPPS, there are various examples of HAT. One application example for physical autonomous systems are self-driving vehicles. These are characterized by different levels of automation. According to a classification by the Society of Automobile Engineers (Society of Automotive Engineers International (SAE), 2018), such vehicles can be divided into levels from 0-5, where 0 means "no driving automation" and 5 means "full driving automation" (Society of Automotive Engineers International (SAE), 2018). The corresponding intermediate levels are described by driving assistance systems, conditional or partial autonomous driving, as in the case of distance assistance systems or driverless parking (Mercedes-Benz Group, 2020). According to a transfer to the levels for the classification of HAT according to O'Neill et al. (2020), self-driving vehicles can be described as HAT at level 3, i.e., as soon as the control is autonomous and the human driver only intervenes when asked to do so (Hagemann & Rieth, 2021). In addition to self-driving cars, the idea of a self-driving vehicle in the sense of a HAT also includes the idea of non-personal usages, such as truck platooning (ADAC, n. d.), self-driving buses (Hansen, 2018), subways, or transport vehicles from the military and space sectors.

Digital assistants such as Apple's Siri, Amazon's Alexa, or Microsoft's Cortana, which can now be found on many mobile devices and smart home devices, are an example for cognitive autonomous systems (Brill et al., 2019). Such an Intelligent Personal Assistant (IPA) is an application that uses the user's voice, the field of view, or contextual information to assist by answering questions, recommending actions, or performing actions (Hauswald et al., 2015).

These examples can already be transferred to application scenarios within production and logistics. As already described in Section 1, collaborative robots, autonomously driving floor vehicles in intralogistics, or intelligent cognitive assistance systems, for example, can fulfill the definition of a HAT. They show implementations of Industry 4.0/5.0 concepts that include autonomous systems and thus HAT. Thereby, an increasing tendency of this kind of collaboration between humans and machines can be assumed for the future. The consideration of previous findings on HAT in the context of this research work shows that basic research and initial design principles are available but that there is a need for further research with regard to interface design and the human-oriented design of autonomous systems.

Overall, in particular, a transfer of the approaches to different CPPS use cases seems necessary to achieve a detailing of the existing design recommendations, e.g., according to Schelble et al. (2020). This includes the following research goals and questions:

1. As outlined in (Quandt et al., 2022, in print), user involvement ensures that the system represents the users' activities and considers the users' needs (Preece et al., 2015). This involvement leads to an increased sense of responsibility of the users for the system design, a higher user loyalty to the developed system, and a resulting higher system acceptance (Wagner & Piccoli, 2007). In this sense, a HAT should be easy to learn, useful, functional for the particular work context, and at the same time easy and enjoyable to use for the operators. To achieve this, an early focus on users and tasks, empirical measurement, and iterative design are necessary (Gould & Lewis, 1985). These three principles are considered the widely accepted fundamentals for human-centered system development (Preece et al., 2015). We assume a similar beneficial effect for the design of HAT in CPPS. Explicit integration of human factors or existing human-centered design (HCD) approaches opens up the potential for improving HAT system performance, e.g., in the areas of transparency or degree of autonomy.

2. As outlined in (Stern & Becker, 2019), a standard research method of human factors are experimental studies (Jacko et al., 2012). These methods can be used to show whether there are causal relationships between the design of a HAT and resulting effects on operator or the system itself. Therefore, in an experimental study, one or more variables are modified in order to induce observable effects studies (Jacko et al., 2012; Wickens et al., 2014). Thus, conducting laboratory studies (and later field studies) for CPPS use cases could help to improve the data foundation and derive more focused design recommendations for HAT.

3. HAT in CPPS could contribute to resource and energy savings in terms of sustainability goals and should therefore be included as a goal early in the development process. In addition, an improved division of labor between humans and machines allows operators the opportunity for creative development and further process improvement since they are released from the cognitive workload of tasks that can be automated, for example.

4. The use of VR environments could promote the use of HAT and the development of corresponding potentials. For example, the utilization of a VR environment instead of an actual test setup is promising for the implementation of studies, which are necessary for a more focused individual design of HAT according to a particular use case. Thus, a pure VR

implementation could significantly reduce development efforts and eliminate the need to develop an actual HAT for testing purposes. Furthermore, such a VR environment could be used for training in using case-specific or higher-level setups to generate knowledge within the workforce for working with autonomous systems.

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