Towards sustaining human-centered part manufacturing under workforce restrictions

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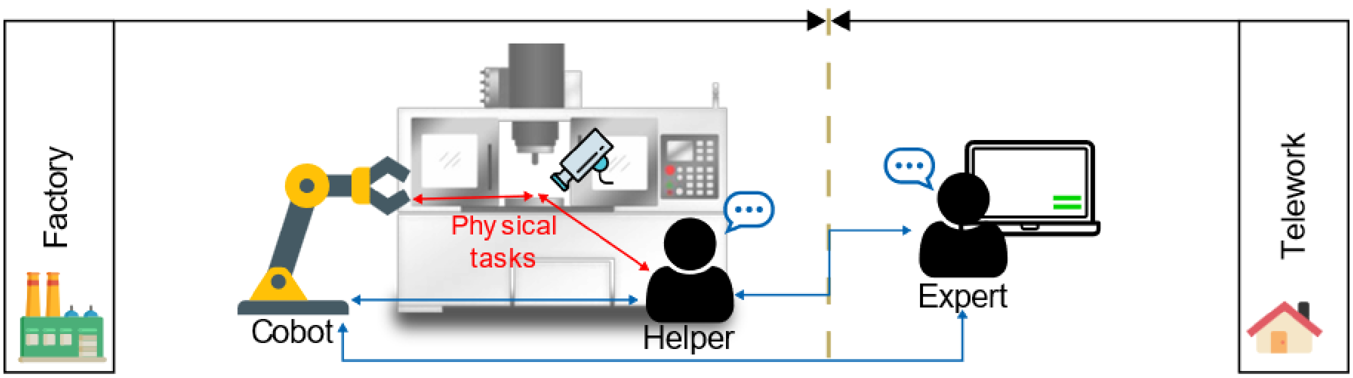

Figure 1: Example system to enable new collaboration modes to maintain part manufacturing (red are physical tasks, blue are virtual)

ABSTRACT

Part manufacturing is a key element of industrial production, in which a variety of manufacturing processes can be performed without manual human activities due to automation. However, human tasks (e.g., machine setup and monitoring) are still required to ensure continuous operation and part quality. Thus, part manufacturing is susceptible to reduced workforce situations (e.g. pandemics). Several technologies potentially enable new modes of collaboration based on interactive systems (remote assistance, remote maintenance, collaborative robots, and teleoperation) where an on-site worker and/or collaborative robot collaborates with a qualified remote worker. Due to the high complexity of the collaborations, a high usability needs to be the predominant goal during design. The Human-Centered Design (HCD) approach, which has not previously been adapted for this purpose, provides a suitable foundation to overcome existing limitations. Therefore, research needs to investigate how HCD can be adapted to design and realize collaboration systems that enable telework in part manufacturing and similar complex industrial environments to handle workforce reductions due to pandemics or staff shortages.

CCS CONCEPTS

• **Human-centered computing** → **HCI theory, concepts and models**; **Graphical user interfaces**; **Interaction techniques**; **Displays and imagers**.

KEYWORDS

Part manufacturing, Telework, Collaboration, Human-centered design

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1 PROBLEM STATEMENT

Industrial production generally consists of the subsequent activities of part manufacturing and assembly. While part manufacturing is defined as the manufacturing of individual parts for subsequent assembly or direct delivery to customers, assembly encompasses putting together a final product from finished individual parts or partially assembled units [29]. One of the prevalent ways of part manufacturing is machining (e.g. milling, turning, and drilling). As of today, machining operations in part manufacturing are mostly performed automatically on machine tools which are equipped with computer numerical control (CNC) that process part-individual computer program, containing all required manufacturing operations [18]. Additionally, part manufacturing tasks are often performed on machining centers (multi-machine operation for higher productivity), which extend the abilities of CNC-based machine tools and enable both unattended operation for a significant amount of time [8] as well as permit one person to operate several machines in parallel. This is possible due to several characteristics: Part-storage systems that contain both raw and finished parts enable continuous operation for several machine cycles. In addition, automated transfer between the storage systems and the machine removes the necessity of manual part feeding. Automated tool changers furthermore allow to perform a variety of machining operations with different cutting tools in one setup. In consequence, machining centers are able to continuously manufacture parts with several machining features within one setting and machining cycle without the necessity of manual operations. This makes machining centers suitable for large series part manufacturing, e.g. in the automotive industry [18].

Despite this high degree of automation of the actual part manufacturing, certain recurring human activities are still required to maintain productivity of the production system and to ensure the quality of the manufactured parts [8]. For example, before a part series can be manufactured on a machining center, initial changeover and setup tasks, such as writing and testing CNC programs, calibrating the machine, or measuring and adding tools to the tool changer, need to be executed [30]. Setup tasks are required only once per series but may take a significant amount of time and therefore, their execution time has a direct influence on productivity [25]. After setup, human activities mostly focus on monitoring and maintaining the regular operation. This includes recurring supply and removal of raw parts and finished parts to and from storage systems as well as routine monitoring tasks, which e.g. include visual detection of missing and broken tools, as well as auditory detection of anomalies (e.g. chatter) [26]. In addition, the quality of manufactured parts, e.g. by routine measurements is ensured by operators as well, including problem-specific reactions to deviations. This may include e.g. the adjustment of tools or fixtures and requires cognitive skills. In addition, liquids, lubricants and consumables have to be replaced manually, which also applies to tools that have exceeded their service life. Additionally, the positional controls have to be checked for offsets that may have developed over time. The equipment needs to be cleaned and chip removal might be required [30]. In case of detected disturbances (e.g. a crash), measures have to be taken to bring the machining center back to regular operation. The above described tasks occur rarely and often vary between executions [5]. Also, they combine cognitive and physical operations and require human expertise [14]. These influences, and the required flexibility and adaptiveness, make the tasks that ensure part manufacturing hard to automate and strongly reliant on the physical presence of human experts.

Productivity and quality problems as well as machine downtimes are likely to result if these tasks are omitted during the absence of experts. This effect manifested in the COVID-19 crisis. To contain the pandemic in manufacturing facilities, common recommendations included to encourage workers to stay home if they are sick or to establish flexible work hours like staggered shifts [19]. Some countries even forced all workplaces to temporarily close down to prevent infections within the workforce. Furthermore, imposed quarantine of people that might have been exposed to COVID-19 intensified workforce absence. Workforce availability and productivity challenges resulted [1]. Part manufacturing is strongly impacted due to the dependence on a small number of experts. Even few absent experts reduce the available workforce and fulfilment of the described tasks significantly. Besides COVID-19, this applies to annually recurring outbreaks of influenza and future pandemics as well, in which similar measures (e.g. social distancing and telework) are taken to prevent distribution [3]. Other industries (e.g. IT) overcome these challenges by relocating staff to telework. Applying this principle to part manufacturing, productivity could be maintained even with reduced on-site workforce. Despite these potentials, manufacturing shows comparably low application of telework, which results from the required physical manipulations on-site [7].

The research described in this paper is conducted in the context of the "$PartRe^2Work$" project. The aim of this project is to investigate how part manufacturing has to be organized and technical appliances in this context have to be designed to support an increased amount of telework in this area. For example, some monitoring or assistance tasks can currently be performed remotely in multi-machine operations across multiple sites. However, there is potential to go further by relocating the staff remote and not onsite. From the point of view of HCD, this is especially challenging as the technical appliances incorporated in such manufacturing systems are extremely heterogeneous and possibly require different approaches of investigation. Nonetheless, these systems have to be integrated into a coherent whole. Traditional approaches adopted by HCD might have a limited usefulness. The goal of the "$PartRe^2Work$" project is to develop and evaluate a framework providing guidelines for manufacturers to partially relocate on-site manufacturing tasks to telework in reduced workforce situations. To achieve this goal, novel methods of doing usability evaluations of systems in part manufacturing have to be developed.

2 STATE OF THE ART

Current research in this context can be grouped into four directions: Remote assistance studies methods to enable assistance by remotely connecting two persons. Remote maintenance addresses the remote collaboration of an on-site user with an expert for maintenance and service processes. Cobots enable to collaborate with humans within a shared space, or where humans and robots are in close proximity. Lastly, teleoperation of machines focuses on controlling and monitoring machine tools without direct physical access.

Regarding remote assistance, AR is used in a framework for assembly tasks which is validated with user studies [9]. Additional approaches describe requirements for an AR-based framework including local cameras with the goal of assisting on-site personnel regarding problems on a machine where a remote operator accesses the machine's CNC control interface [22]. As handling disturbances is an essential task in part manufacturing, remote maintenance is of relevance for the envisioned approach. Here, technicians remotely collaborate with users on-site to assist with maintenance tasks. One approach proposes a method to perform monitoring and maintenance remotely. Maintenance tasks are however limited to accessing digital machine information to prepare visits of service personnel [15]. Furthermore, machine monitoring data is coupled with AR to enable remote maintenance [16]. Furthermore, a remote maintenance system for a machine tool based on AR and audio communication is described by Vorraber et al. [27]. Cobots show potential for the envisioned collaboration modes, since cobots are impervious to being infected and their productivity would not be affected during a pandemic. Furthermore, cobots allow scenarios, in which a remote user uses a cobot on-site for physical manipulations (e.g. [13]). However, creating part manufacturing collaboration modes by integrating machines, cobots, information or communication systems and humans inevitably leads to questions, how and in which way adequate task sharing takes place [2]. Literature shows several strategies, such as only assigning those tasks to a robot that cannot be humanly performed or distributing the tasks with the aim of the lowest cost [6]. Considering new forms of collaboration between humans, machines, information and communication systems, further strategies can be expected with new requirements regarding the design of new teleworking methods and possibilities along the human-technology-organization concept. These requirements should be derived, investigated, and analyzed regarding use cases with the goal of an efficient balance between a productivity and human centered oriented set up. Altogether, symbiotic human-robot work systems provide an auspicious setting for new modes of collaboration under uncertain access conditions, but still need grounded research with special emphasis to the integrated and user-centered design and development of assistance systems. Teleoperation of machine tools potentially enables telework access to machines and is the subject of several approaches that, for example, allow a remote user to monitor the absolute and relative motions of all axes as well as to control the spindle speed and feed rate of a machine tool [28]. The implementation of a remote system for the manufacture of turned parts is also described. In this work, continuous visual feedback with cameras is streamed and remotely controlling a CNC machine is allowed. Manual tasks on-site that exceed the scope of the CNC control are not considered [4]. Furthermore, remote monitoring and control of a CNC machine tool are investigated by Oliveira et al. The approach is limited to functions of the control panel (e.g. "Start program"). Tasks that are described above and require manual operations are not considered [20]. Rogowski aims at remotely controlling and programming machine tool features like auxiliary devices or loading CNC programs. In addition, a camera provides visual feedback of the machine state to the teleoperating user. The interaction with the machine is however not suitable for the described tasks in part manufacturing, as an asynchronous approach is chosen, in which specific CNC programs are submitted remotely which are subsequently executed [23]. In the envisioned context, on-demand, synchronous control inputs are required.

Research from the four research directions partly addresses questions that arise when investigating telework modes for part manufacturing. However, none of the approaches in these fields is capable of performing all required activities: Remote assistance methods mainly aim at assisting in physical tasks, mostly from assembly. Assisting in machining operations is rarely considered in implemented approaches. Even though the necessity was pointed out [22], no approach shows a systematic integration of remote assistance with remote control that would enable the remote expert to directly interact with the machine without having to communicate complex tasks to the helper, which would reduce the chance of errors. Remote maintenance approaches also omit to exploit the potential that lies in remote machine control. While maintenance is a crucial task, remote maintenance approaches aim at customer service, which implies that the remote expert is a qualified service employee, trained in the remote interaction with on-site users. In contrast, the envisioned expert-helper collaboration has to be ramped up in exceptional situations that occur suddenly and are not daily routine for those involved. Hence, the systems and modes of collaborations need to be specifically designed for this purpose including a high usability for intuitive operation and fast ramp-up. This is not explicitly covered in existing remote maintenance approaches. Additionally, cobots provide beneficial elements to support part manufacturing under reduced personnel constraints. Existing approaches are however limited to physical interactions and do not cover other aspects of part manufacturing. Current approaches therefore only partly address the needs of the described collaboration forms. Integrating cobots in such constellations further raises unsolved questions of human-cobot task distribution. Machine tool teleoperation approaches in part manufacturing also encompass single aspects of the envisioned collaboration modes, such as remote monitoring and interaction, as well as video surveillance of the machine's current state. Such approaches are however limited to tasks that can be performed via the machine's control system and exclude all manual tasks on-site. Despite video feedback, the remote expert cannot interact with the machine (e.g. manual adjustment of a fixture).

In addition, no previous approach addresses the problem of reduced workforce in part manufacturing. Even if the foundations from the four research directions can be integrated, the resulting interactions between the humans and the technical systems needs to be specifically designed for this purpose. Collaboration can become complex, unpredictable and undetermined as a result of different skills of those involved, the heterogenous character of the tasks, and the integration of digital technologies. This leads to a complex solution space, from which the envisioned collaboration modes need to be designed. In this context, research needs to find ways of mastering this complexity and achieving the goal of maintaining part manufacturing operation, which might be attained through human-centered design.

3 HUMAN-CENTERED DESIGN IN MANUFACTURING

It is becoming increasingly apparent that a high level of usability via HCD is the key to success not only for IT systems, online services, and telecommunications products but also the manufacturing and industrial sectors [21]. There exist some research works that apply HCD in the realms of manufacturing: Semi-structured interviews were conducted with companies to assess the impact of the application. The research project "AuQuA" applies HCD for the development of assembly support systems [31]. A similar focus is chosen by Römer et al. who also develop an assembly assistance system [24]. Another approach develops production planning and control assistance systems using the HCD framework [17]. In the work of Kluge et al., the design of a fault-finding application for manufacturing is described [12].

In general, the growing influence of the Industry 4.0 principle in production systems entails an amalgamation of technologies such as virtual environments, unstructured data, and complex simulation models, and all this latest industrial automation must be integrated with human capabilities. This has led to the Human-Centered Manufacturing (HCM) movement, which integrates the strength, efficiency, repetitiveness, and precision of automation with the knowledge, versatility, and ability of human operators resulting in hybrid systems of tremendous potential in terms of manufacturing processes and safety for employees [21]. Despite the potential and importance of HCD and usability, to date only a limited number of approaches apply HCD in manufacturing. No approach focuses on part manufacturing.

4 DISCUSSION AND FUTURE WORK

To take into account the above-mentioned potentials and challenges a proof-of-concept framework is being developed to apply HCD principles for part manufacturing telecollaboration modes [11]. The referenced work provides a first look at how specifications may be derived and design solutions formed, however, it also highlights some of the issues.

One of the main challenges is the evaluation of technical innovation in the field of part manufacturing, especially the evaluation from a human-centered point of view. Because of the tight schedules in part manufacturing, it is often difficult to conduct evaluations with company employees. Evaluation methodologies like extensive user studies or more experimental approaches can interfere with work processes. Therefore, interviews or focus groups are often adopted in such situations. Nevertheless, conducting interviews in this context might be difficult. The possibilities to support telework in part manufacturing are quite diverse and heterogeneous. Answers in such interviews, therefore, tend to be very general and contain only very abstract information. This makes it difficult to develop concrete guidelines or recommendations on how to introduce telework in part production.

Researchers from the area of User experience (UX) suggest using contextual inquiry, a mix of interviews and observation, to identify the requirements for work processes and the advantages of the adoption of novel technologies [10]. They argue that it is not sufficient to conduct interviews because workers are often not consciously aware of requirements and possibilities of novel technologies. Observation can uncover requirements of the work processes not yet identified by stakeholders. In this context, a holistic approach should be adopted [32]. Zigart et al. propose to use multi-criteria evaluation models, encompassing economic, technical, and user related goals. Future work should test the practicability of this approach and check whether the information gained in this way is able to provide a foundation for concrete recommendations or guidelines for the implementation of telework in part production and similar industrial environments.

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