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Engaging human-centered design to maintain part manufacturing under reduced workforce restrictions

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Abstract

A central element of industrial production is the manufacturing of finished parts from raw material. Even in highly automated environments, processes like milling still rely on human intervention. On-site human operators play a crucial role in ensuring the continuous operation and quality of parts through tasks such as setup and maintenance. This reliance on human involvement makes part manufacturing vulnerable to workforce reductions, whether due to unforeseen circumstances like pandemics or staff shortages. However, new modes of telework collaboration based on interactive systems that comprise visualization and communication technologies, collaborative robots, fast internet, and remote control of machine tools bear potential to overcome these challenges. In consequence, a conceptual framework is proposed that investigates how such modes and systems need to be designed to share the respective tasks between teleworking and on-site employees. As the interactions and systems show a high complexity and since reduced workforce situations often occur suddenly, a high degree of usability must be ensured to enable quick ramp-up and reliable operation. Therefore, an interdisciplinary approach between manufacturing engineering, ergonomics/human factors and human–computer interaction investigates how the concept of human-centered design (HCD) needs to be adapted to ensure this usability. While the initial study focuses on how to integrate human workers in the design of such a system, it also highlights the need to examine different collaboration modes and application scenarios.

Keywords Part manufacturing · Telework · Collaboration · Human-centered design

1 Introduction

Industrial production generally consists of the subsequent activities of parts manufacturing and assembly. As of today, machining operations in part manufacturing are mostly performed automatically on machine tools equipped with computer numerical control (CNC) that process part-specific computer programs containing all required manufacturing operations. Especially when manufacturing larger series, a higher degree of automation is applied. This includes the usage of machining centers, which extend the capabilities of CNC-based machine tools and enable unattended operation for a significant amount of time due to part-storage systems, automated material transfer, and automated tool changing. Consequently, machining centers can 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.

While part manufacturing with lower automation degrees requires a high share of manual tasks (e.g., part removal or

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starting CNC programs), even highly automated scenarios still depend on certain recurring human activities to maintain productivity and to ensure the quality of the manufactured parts [1]. Before a part series can be manufactured, 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 [2]. Setup tasks are required only once per series but may take a significant amount of time and therefore lower productivity of the cell [3]. Productivity and quality problems as well as downtimes are likely to result if these tasks are omitted during the absence of experts. Because of these dependencies, the manufacturing of parts becomes highly vulnerable to situations where the workforce is diminished, such as during pandemics or staff shortages.

To counteract times of reduced workforce (i.e., during the COVID-19 pandemic or similar) other industries (e.g., IT) overcome these challenges by relocating staff to telework. By applying this principle to part manufacturing, productivity could be maintained even with a reduced on-site workforce. Despite these potentials, manufacturing shows comparably low application of telework, which results from the required physical manipulations on-site [4]. Even after being directly confronted with the impacts of such staff shortages, almost no manufacturer implemented concepts like “home factory”, where manufacturing tasks are partly performed from home [5].

Several concurrent technological developments provide promising possibilities to overcome these challenges by enabling telework and collaboration in part manufacturing. Modern machine tools and machining centers offer remote access to control panels including status information and, in some circumstances, remote control [6]. Furthermore, web-based cameras and technologies like Augmented Reality (AR) enable interactive visualization of respective points of interest. This is important since the performance of collaborative tasks is increased if the visual context is shared: Coordination is improved, and a common understanding is established more easily [7]. Communication-based on direct verbal and visual synchronous communication technologies further promotes remote collaboration [8]. Regarding physical interactions, advances not only in AR and robots [9] but also collaborative robots (cobots) [10] enable remote operation or dividing tasks between cobots and humans. Integrating these technologies could enable telework in part manufacturing by forming new modes of collaboration in which manufacturing employees in telework collaborate in varying degrees with human colleagues, supported by additional technologies on-site to perform the required human tasks.

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 collaboration with humans within a shared space or where humans and robots are nearby. Lastly, *teleoperation of machines* focuses on controlling and monitoring machine tools without direct physical access.

Regarding remote assistance, AR is used in a validated framework for assembly tasks [11]. Other studies also focus on assembly tasks using AR [8]. Additional approaches describe requirements for an AR-based framework, including local cameras to assist on-site personnel with machine problems [6]. Remote maintenance and monitoring methods are proposed, but limited to accessing digital machine information [12]. Some approaches combine machine monitoring data with AR for remote maintenance [13]. A tablet-based AR system is outlined for remote maintenance [14], and another system incorporates audio communication [15]. Cobots show potential for collaboration, especially during a pandemic [16] , however, questions arise regarding adequate task sharing [17]. Literature suggests strategies such as assigning non-humanly performable tasks to robots or distributing tasks for cost efficiency [18]. The goal is to achieve an efficient balance between productivity and a human-centered setup. Symbiotic human-robot work systems offer opportunities for collaboration, but further research is needed for integrated user-centered design of assistance systems. Teleoperation of machine tools allows remote control, including monitoring motions and controlling speed and feed rate [19]. Nevertheless, certain manual tasks on-site are not considered [20]. Remote control and programming of machine tool features are proposed, but the interaction is asynchronous [21]. On-demand, synchronous control inputs are required for the envisioned context. Existing research addresses telework modes for part manufacturing but fails to cover all required activities. Remote assistance mainly focuses on physical tasks, while remote maintenance approaches neglect remote machine control. Integrating cobots raises questions about task distribution. Machine tool teleoperation approaches only cover specific aspects and exclude manual tasks.

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 can perform 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 [6], no approach shows a systematic integration of remote assistance with remote control that would enable the remote user to directly interact with the machine without having to communicate complex tasks to the on-site workforce, 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 workforce is a qualified expert service employee, trained in the remote interaction with on-site users. In contrast, the envisioned remote-on-site collaboration has to be ramped up in exceptional situations that occur suddenly and are not daily routine for those involved. Hence, a novel system and new modes of collaborations need to be specifically designed for this purpose including a high usability for intuitive operation and fast ramp-up.

In addition, no approach addresses the problem of reduced workforce in part manufacturing. Even if the foundations from the four research directions can be integrated directly, the resulting interactions between humans and technical systems need to be specifically designed for this purpose. Collaboration can become complex, unpredictable, and undetermined due to different skills of those involved, the heterogeneity of the tasks and the integration of digital technologies. This leads to a complex solution space, from which the collaboration modes need to be designed. In this context, our paper sheds light on how to master this complexity through the integration of human workers in the design of the resulting systems and collaboration modes, which is the focus of HCD.

In consequence, an interdisciplinary approach is proposed that investigates how the concept of HCD needs to be adapted to ensure continuous operation and part quality of manufacturing tasks under reduced workforce restrictions. The remainder of this paper is structured as follows: in Sect. 2 we look at the fundamentals of the HCD process and its applicability to manufacturing, then in Sect. 3 we look at the individual steps in the HCD process, we move on with applying the HCD process in part manufacturing in Sect. 4 and conclude with Sect. 5.

2 HCD fundamentals and relevance to manufacturing

2.1 Challenges of developing collaboration modes

No single approach addresses the problem of reduced workforce in part manufacturing. Even if the foundations from the above-mentioned four research directions can be integrated, the resulting interactions between humans and technical systems need to be specifically designed for this purpose. Existing research and case studies highlight how collaboration can become complex, unpredictable, and undetermined due to different skills of those involved, the heterogeneity and uncertainty of the tasks, and the integration of digital technologies [22]. This leads to a complex solution space, from which the collaboration modes need to be designed. This also needs to consider the influence of varying part manufacturing scenarios in industrial settings (e.g. automation degree or lot sizes). In this context, research needs to find ways of mastering this complexity and achieving the goal of maintaining part manufacturing operation. This requires the integration of human workers in the design of the resulting systems and collaboration modes, which is the focus of human-centered design.

Regarding the design of technical systems, businesses across a wide range of industries are transitioning from a technology-driven approach to an incorporation of the user in the design process [23]. However, in manufacturing, the establishment of new work systems often focuses on engineering functionality rather than on usability and user experience. With regards to telework in part manufacturing, this tendency can be seen in the existing approaches which focus mostly on technological rather than the human aspects [24].

However, recent developments in manufacturing have led to better incorporation of users and operators: as more and more processes are being automated, humans are still required for complex tasks that require cognitive thinking and adaptivity, such as in the described part of manufacturing activities. In combination with the growing sophistication and interconnectivity of devices in the context of Industry 4.0 [25], the need to concentrate more on the user, the work task, and the work environment is expected [24]. This work aims at emphasizing this human performance (e.g. comfort perceived, physical and mental workload, simplicity of actions, and personal satisfaction [26]) during the design of new interactive collaboration systems to master reduced workforce situations while ensuring high productivity and process quality. These aspects lead to the field of usability and HCD.

2.2 Usability and HCD

Usability can be described as the capacity of a system to provide a condition for its users to perform the tasks safely, effectively, and efficiently while enjoying the experience [27]. It has already become an established field of activity in software or digital products [28], and is increasing in importance in the field of physical consumer and commercial products as well [24]. To highlight the benefits of a system with high usability, the characteristics of poorly designed and unusable systems are pointed out. In the context of this work, this implies that the teleworking and on-site employees would have problems in their interactions. In consequence, as case studies have already shown [29], frustrated users may maintain their current working methods at the expense of systems that are underused, misused, or disused. This may lead to safety problems since the users on-site interact with moving machine parts. Furthermore, if the collaboration cannot be performed properly, the fulfillment of the tasks cannot be guaranteed, and productivity or quality problems might arise.

When overcoming the described challenges, well-designed and highly usable systems show benefits regarding industrial applications [30]: *Increased productivity*—a usable system should allow the user to focus more on the task rather than the tool; *reduced errors*—a well-designed interactive system can help to prevent inconsistencies, ambiguities, or other flaws in interface design; *reduced training and support*—a usable system can improve learning and help reduce the need for training or assistance; and *improved acceptance*—often an indirect outcome of a usable system where users want to use and trust a well-designed system the most.

A framework that aims at systematically ensuring usability during design is HCD, which is an approach to creating interactive systems that seek to make systems useful and functional by focusing on users and their demands and requirements [31]. The human-centered approach ensures highly usable systems and products that tend to be more successful by increasing efficiency and effectiveness, accessibility and sustainability, and counteracting the negative health, safety, and performance influences that could result from using the system [32].

Critics say that the extreme emphasis on customer needs limits developers' perspectives and prevents meaningful technological progress [33]. Similarly, some assert that people's lives and circumstances are rapidly changing, and therefore any observations and surveys are pointless unless a product is built quickly. Further, critics also argue that it places too much emphasis on context and stakeholders, making it unsuitable for producing customized solutions for a specific target group.

However, in the context of this work, research (e.g. [34] or [24]) shows the principal applicability of the HCD approach in industrial settings, as individual human performance (e.g., perceived comfort, physical and mental workload, simplicity of actions, personal satisfaction) and how hazardous positions and uncomfortable tasks finally cost an industrial plant affecting its costs, productivity, and process quality. It is due to such reasons that our research is based on HCD.

Combining telework collaboration with traditional manufacturing processes using a human-centered approach bears the potential for substantial economic and social benefits for both users and employers. In particular, user focus during the development from start to finish helps increase the productivity of users and the operational efficiency of organizations.

2.3 HCD in manufacturing

The benefits of HCD can be achieved even before product creation and process definition to assist in the reduction of production times and help avoid late optimization loops [35]. Companies can also avoid bad workplace ergonomics that can harm productivity, quality, safety, and costs [34]. Therefore, numerous research works apply HCD in the realms of manufacturing: The project "AuQuA" applies HCD for the development of assembly support systems [36]. A similar focus is chosen for the development of the assembly assistance system [37]. Another approach develops production planning and control assistance systems using HCD [38]. In the work of Kluge et al., the design of a fault-finding application for manufacturing is described [39]. In general, the growing influence of the Industry 4.0 principle in production systems entails an amalgamation of technologies such as virtual environments, data processing, and simulation models, and all this latest industrial automation must be integrated with human capabilities. This has led to the Human-Centered Manufacturing (HCM) [40] paradigm, 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 [41]. 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 or machine tools in general.

3 Methods to support HCD

User focus during the development from start to finish helps to increase the productivity of the users and the operational efficiency of organizations. HCD achieves these goals through a four-stage process (see Fig. 1) that begins with the project start and iteratively goes through (A) understanding and specifying the context of use, (B) specifying the user requirements, (C) producing design solutions, and (D) evaluating the design [32].

3.1 Planning the HCD process

The ISO 13407 standard [32] details what the HCD process should entail. This process begins by defining the HCD process, which involves two steps: usability planning and scoping and usability cost-benefit analysis. The first step entails bringing the stakeholders of the project together to discuss and reach an agreement on how to prioritize usability and how usability can contribute to the goals and objectives of the project. After this comes the second step where it becomes necessary to study and assess the potential benefit to be gained from including the HCD process activities within the system or software development lifecycle as well as which methods to be used and can be afforded by the budget of the project [30].

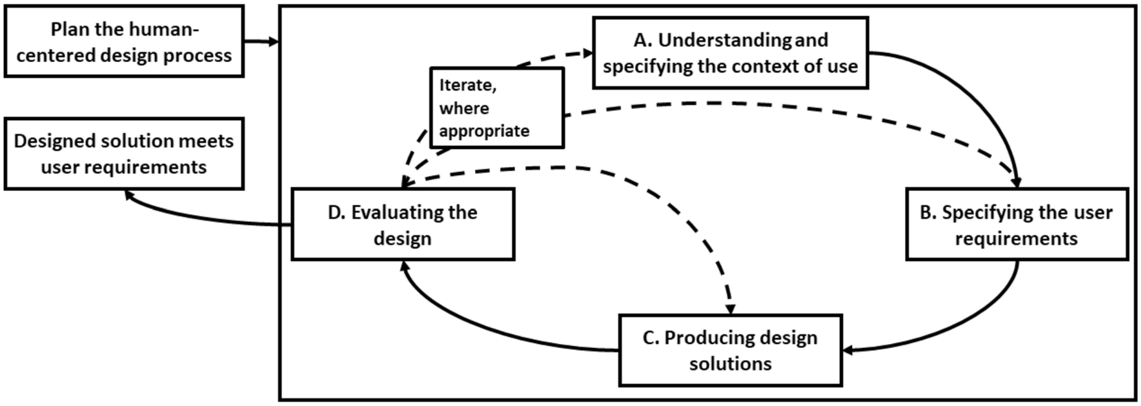

Fig. 1 HCD for interactive systems based on ISO 9241-210 [32]

Here, the system is used within various range of technical, physical, or organizational conditions that may affect its use.

3.2 Understanding and specifying the context of use

The quality of the use of a system being developed, with emphasis on usability, user's health, safety, and reliability depend highly on understanding and specifying the context of use of the system. For example, in a part manufacturing environment, there are many factors to be considered that could impinge on the usability of new software product (e.g. ease of use, availability of support, user's workload, efficiency, perceived value etc.). Therefore, capturing the system's contextual information is important to aid in the specification of requirements, designing a solution, and providing a sound basis for a later evaluation.

The following methods could be used or combined to understand and specify the context of use: identify stakeholders, context-of-use analysis, a survey of existing users, user observation, task analysis, and Diary Keeping [30]. To develop a well-understood system in this paper, identifying stakeholders and performing a context-of-use analysis method have been used to sufficiently understand the context of use of the system.

Requirement elicitation and analysis are of major significance to the successful development of software, and it is widely accepted to be the most crucial part of software development [42]. To perform requirements elicitation and analysis, effective communication and collaboration between the stakeholders are necessary. A survey conducted demonstrated the two major causes of system failure were: insufficient effort to establish user requirements and lack of user involvement in the design process [43]. This emphasizes the importance of requirements specification from a human/user-centered approach as these problems highlight a failure to recognize the needs of the system user as well as incorporate them with the system development process.

Various methods can be used to support user and organizational requirements specification and elicitation, but the following methods were applied: Stakeholder analysis [44], User requirement interview [45], Allocation of function [32], and Task/function mapping [30].

3.3 Producing design solutions

Design solutions for a system could take many forms; from copying and development, by logical progression and updates from previous designs, through to creative innovations. Worthy of note is that whatever the source for the design is, all design ideas, or solutions as they are formed, progress, and put together go through an iterative development lifecycle. This iterative process provides room for improvement and growth, and these changes to the design may be rapid in response to the user or evaluator feedback as this helps to avoid the costly process of the entire system rework or correcting of design faults in the later stages of the development cycle of the system [30]. For example, correcting issues discovered after the product has been deployed can be exceedingly expensive and risky, costing substantially more than correcting them early on. Additionally, making code modifications to repair a bug can have an influence on the application's functionality, necessitating more changes and raising the cost, time, and effort required [46].

The following list of methods were included amongst others in the various techniques for generating ideas, new designs, and producing a design solution: Brainstorming [47], Storyboarding [30], and Paper prototyping [30].

3.4 Evaluating the design

Finally, evaluation is a very important activity within the system development lifecycle, so designs should be

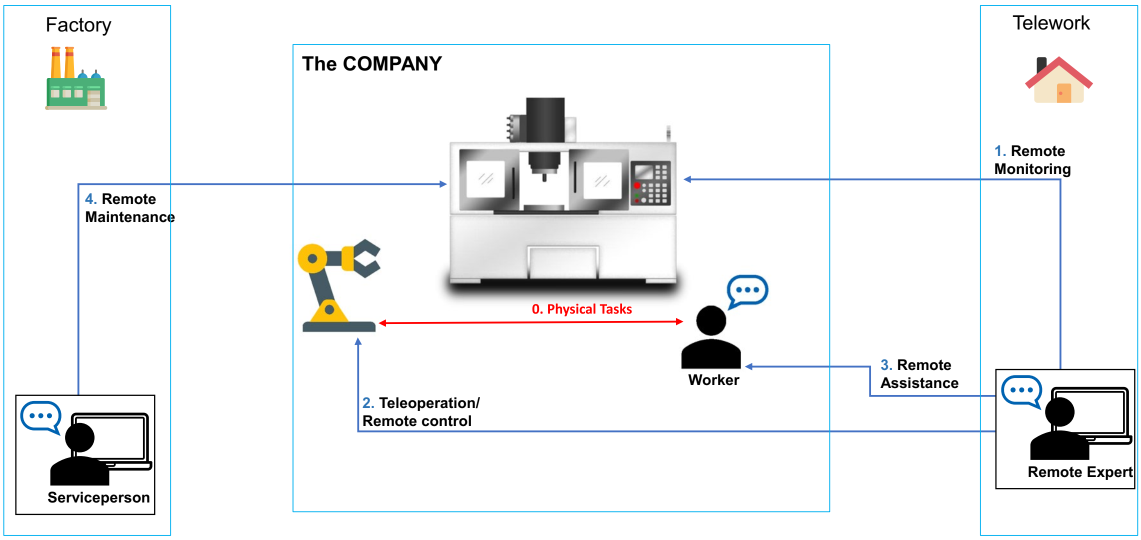

Fig. 2 Overview of proposed system

evaluated against requirements throughout development as it can confirm how far and well user needs and organizational objectives have been met and provide useful information for refining the design. It is good practice and advisable to carry out evaluations and receive feedback from the user from the earliest opportunity as with other human-centered activities before making changes becomes relatively expensive. Formative and summative testing are the two main reasons for carrying out usability evaluation of designs against requirements. Formative testing is done to improve the product or system as part of the development process usually by identifying and fixing usability problems while summative testing is carried out to find out whether people can use the product successfully [30].

Since the focus of this paper is to design a solution rather than designing a software prototype, this paper will be applying formative methods of evaluation. Formative evaluations involve the iterative evaluation of a product a service during the development phase to identify and get rid of any usability problems that arise or may arise [48]. The following formative evaluation methods were used: Heuristic [49] or expert evaluation and Evaluation/usability walk-through [50].

4 Applying the HCD process

4.1 System under investigation

The system described in this paper is an interactive system that enables several collaboration modes to maintain part manufacturing operations. Figure 2 presents a general overview of the system showing the various modules grouped into major components and the way these system components and users interact with the system.

The center of these modules is a machine on which the classic tasks of parts manufacturing are performed. These include among others the processing of raw materials, setup tasks, monitoring tasks, and maintenance tasks on the machine. Depending on the level of automation of the machine, these tasks have the potential to be shifted to teleworking or require on-site personnel. The aim is to ensure that these tasks can be performed even with a reduced workforce. This will be achieved through the implementation of the following four modules.

The first module is the teleoperation of machines using remote monitoring and remote control. With the use of CNC machines, this module allows the remote expert to remotely monitor and control machines giving them instructions usually in the form of algorithms to perform desired tasks. It also enables the serviceperson to remotely monitor the machines during routine maintenance or when maintenance is requested, as well as remotely control the machines to fix any issues found during maintenance.

The second module is the control and collaboration with cobots. The system enables remote experts to remote control the cobots and guides them to perform tasks whether repetitive or dangerous. It also enables on-site workers to control cobots that are on-site to perform physical tasks, and this is another collaboration mode that the system provides. Enabling collaboration of on-site workers with cobots to perform tasks leads to fewer risks when the task to be performed could be dangerous and ensures repetitive tasks and routine checks (using the cobots) are done with 100% efficiency while ensuring quality alongside.

The third module is remote assistance. Remote assistance presents a collaboration mode between the remote expert and the on-site worker. While there are many machines in part manufacturing industry and every machine requires expert workers to operate them and perform tasks with them, this system makes the expert readily available to assist and guide on-site workers with little or no skill and knowledge about a particular machine and its functions on how to perform work and carryout required activities efficiently. Using this collaboration mode, on-site workers can request experts to assist them in any task using several forms of available communication methods and remote experts will provide their guidance to the on-site workers.

The fourth and final module is remote maintenance. Remote maintenance presents another collaboration mode between the serviceperson and the remote expert/on-site worker. This module which also allows a collaboration mode between the serviceperson and expert/- worker occurs when maintenance is requested or during routine maintenance. It enables the serviceperson to remotely monitor and control the machines (within restriction) from the factory where the machines were produced, run necessary diagnostics to ascertain or figure out possible issues, and endeavor to solve them. When the problem to be solved requires input or a necessary task to be performed by the expert, then the serviceperson contacts the expert and guides him on what needs to be done to get the machines back to their optimal performance.

4.2 Requirements specification

The process of obtaining and eliciting the user requirements is rigorous and iterative process which does not only entail obtaining and identifying the requirements but also discussing with the stakeholders to ensure that the requirements identified are the right and important ones [51].

The first step in carrying out the requirements specification of the system was to identify the stakeholders and perform a stakeholder analysis. In the process of analyzing the stakeholders, a list of all the stakeholders that impact the systems was made, and then the level of interest and influence for each stakeholder was determined. The stakeholders are experts, servicepersons, as well as workers. Depending on the mode, some of them may work in telework or on-site. In this paper, however, only the roles of the remote expert or factory serviceperson and the on-site worker are considered. Other roles, such as remote worker and on-site expert, are the subject of further research. The remote expert, on-site worker, and the factory serviceperson are described below:

- On-site workers are physically present to carry out tasks around the workplace and collaborate directly with the cobots. They are physically present on-site to request remote assistance, carry out on-site monitoring, and request remote maintenance for the machines. They request the expert knowledge of remote experts to assist them in performing a particular task when required.
- Remote experts have expert knowledge on how to complete the required task. They perform remote monitoring and control of the machines, requesting remote maintenance, provision of remote assistance, and teleoperation of cobots. Remote experts are available for assistance and guidance of workers, and they will also provide maintenance information to factory serviceperson.
- Factory serviceperson is a type of remote expert who provides maintenance services for the CNC machines. The serviceperson is not an employee of the company but rather an employee of the factory that manufactures the CNC machines used in carrying out physical tasks. He is responsible for routinely maintaining the machines or fixing any issues when maintenance is requested to ensure efficiency and continuous performance. He performs remote monitoring, remote control, and remote maintenance of the CNC machines when maintenance is requested.

Requirement elicitation describes the entire process involved in the identification of the system's exact requirements from start to finish. It is an exploratory and iterative practice of researching and discovering the requirements of a system from users, customers, and other stakeholders.

Some steps and techniques are applied often iteratively to obtain and gather the system requirements for the proposed system. Figure 3 shows the flow of techniques that were applied to obtain the system's requirements which were then documented and specified as functional and non-functional requirements.

These approaches as they apply to the proposed system are described as follows:

- *Stakeholder analysis*: Before carrying out a stakeholder analysis which was the first requirements elicitation technique applied, a context of use analysis was carried out. The context of use analysis was performed to have a sufficient understanding of the context of use of the system which was then used as an input to the stakeholder analysis stage. The stakeholder analysis stage of the requirements elicitation entailed identifying, assessing, and prioritizing the various stakeholders that could impact the system.
- *User requirements interview*: This was an important and helpful approach in obtaining and reviewing the user requirements for the proposed system. After having a good understanding of the context of the use of a system and performing a stakeholder analysis, requirements interview meetings were iteratively carried out.

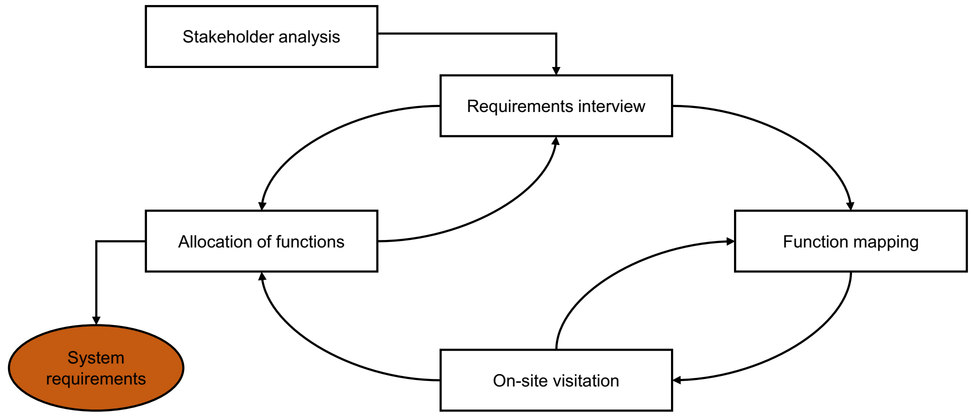

Fig. 3 Requirements gathering approach

The requirement meeting was held with a part manufacturing engineer who possessed expert knowledge of the industry and is a potential user for whom the system is being designed. The requirements interview was done multiple times, continuously discussing, clarifying, and improving the system functions. tasks, and user roles. Discoveries and knowledge obtained about user requirements from the requirements interview served as input for the function/task mapping and allocation of functions.

- *Function mapping*: After performing a stakeholder analysis, the next step was specifying and mapping out the system functions that each user will require for the different tasks that they perform. This was done for each of the users: Specifying the roles, tasks, and functions expected of the user.
- *On-site visitation*: This was an approach that provided an authentic and unique experience of the workspace (where physical tasks occur) and the CNC machines the proposed system would be interacting with. It provided a good perspective to fully understand the CNC machines used in the workplace as well as experience what a typical part manufacturing process entails.
- *Allocation of functions*: This final approach to requirements elicitation entails the division of system tasks into those performed by humans and tasks performed by technology. It combined all inputs and user requirements information acquired from the other approaches such as the requirements interview, on-site visitation, and function mapping to categorize the system tasks and functions into those carried out by humans or technology such as cobots or CNC machines.

The proposed interactive system would enable new and various collaboration modes to maintain part manufacturing operations. It combines the areas of remote assistance, remote maintenance, cobots, and teleoperation of machines. The software system and modes of collaboration are designed from a human-centered approach resulting in a system with a fast ramp-up and high usability which increases productivity, reduces errors, and increases user satisfaction. The integration of AR technology into the systems and processes enables better audiovisual collaboration between the on-site worker, remote expert, and serviceperson. Problems and challenges can be resolved quickly and efficiently by displaying real-time (or saved) 3D annotations on environments and objects.

Research and discussion with an expert proved that it would be very helpful if the system would be available on mobile devices as a mobile application. This mobile application would connect to the internet to perform collaboration and communication between the users as well as be compatible with the CNC machines and cobots on-site.

Further, based on the mentioned methods major functions which the system must perform or must let the user perform are defined. These functions can be further categorized into functional (see Table 1) and non-functional requirements (see Table 2).

4.3 Design implementation

Producing a system design solution entails generating ideas and new designs for a system or product from a set of requirements, to ensure that the product will both be usable and will meet the functional needs of the users. The system software design solution is produced to be used as a mobile application and it was designed using system models such as use case, activity, flow diagrams, etc., and translating these system models into a low-fidelity prototype. Furthermore, the design solution produced for the system covered all the requirements that were gathered in the requirements specification process.

The architecture design of a mobile application is an important consideration for ensuring that the mobile application created is robust, testable, and maintainable. Mobile app architecture entails the sets of rules, guidelines, processes, and patterns involved in the development. Together these sets of rules assist developers in creating an application that meets the user, organizational, and business requirements while ensuring industry standards are being adhered to.

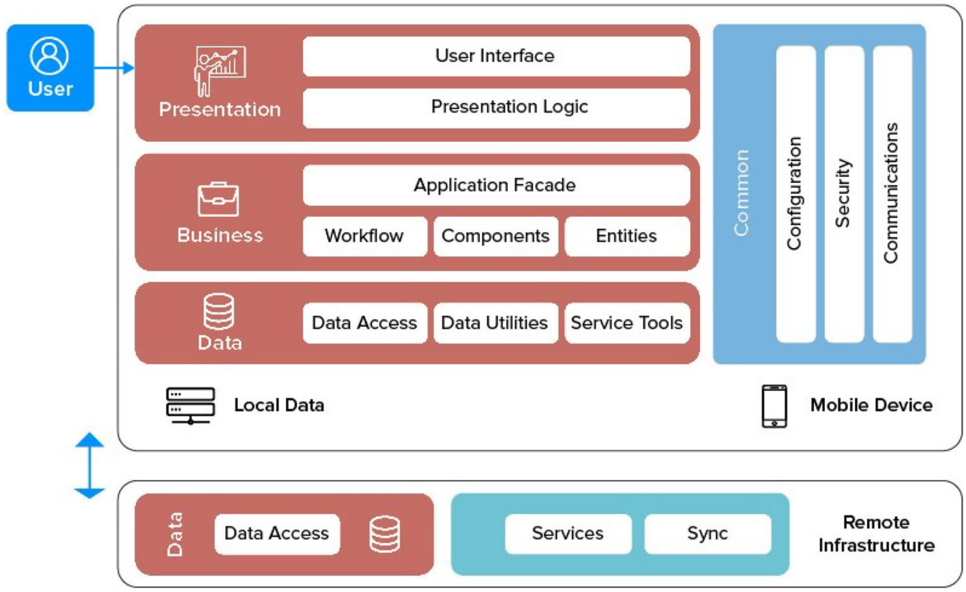

Fig. 4 Mobile application architecture design [52]

Figure 4 shows the architecture design of this mobile application and the following are its three main layers:

The presentation layer comprises of the User Interface (UI) components and the UI process components (views and controllers) [53]. The presentation layer fundamentally consists of all the processes and components required to deliver the application to the user. The end user's mobile application's presentation is the primary focus of this layer of the mobile architecture.

Just as the name suggests, this layer of the mobile application is focused on the elements of the business front. It is concerned with how the application will present the business to the intended users of the system. This layer as can be seen in Fig. 4 and is comprised of components, workflow, and entities. It is concerned with the logic and rules for data exchange and workflow of this mobile application. The business layer of this mobile application exists on both the server and on the user's device depending on the resources required of each operation.

The data layer, which is the third layer of this mobile architecture, includes all the data utilities, service agents, and data access components to support data transactions of the mobile application. This layer of the application meets the application's needs by offering efficient and secure data transactions between the various components of the application. The design of this layer for the mobile application included consideration of validation techniques and maintenance of the data in the application as well as selecting the correct data format.

An actor specifies a role played by a user, entity, or any other system that interacts with the mobile application being designed. These actors could be a person, an object, or an external system that performs a role in this mobile application. The actors of this mobile application are the on-site worker, remote expert, factory serviceperson, cobots, and CNC machines and their roles are highlighted below:

- The remote worker has the following goals:
  - primary actor,
  - approve the request and provide remote assistance,
  - observe machine failure and request remote maintenance,
  - chat with on-site workers and serviceperson,
  - communicate via audio or video call by using AR technology,
  - record the communication,
  - remotely control of cobots,
  - and remotely monitor and control the machine by sending instructions to the CNC machine.
- The on-site worker is primarily engaged with:
  - primary actor,
  - request for remote assistance,
  - observe and report machine failure,
  - chat with remote experts,
  - communicate with experts via audio or video call by using AR technology,
  - and can record the communication.
- The serviceperson has the following objectives:
  - secondary actor,
  - provides routine and requested remote maintenance,
  - chat with a remote expert,
  - communicate with a remote expert via audio or video call by using AR technology,

  - remotely monitor and control machines by running diagnostics,
  - and sending instructions to the CNC machine.

- The cobot is a technology entity with involvement in mobile applications. It collaborates with the on-site worker and can be remotely controlled and monitored by the remote expert to perform physical tasks at the workplace. This actor has the following goals:

  - secondary actor,
  - perform collaborative tasks with on-site workers and remote experts,
  - can be used to perform dangerous, repetitive, and routine tasks,
  - control and monitor the CNC machines,
  - and is remotely controlled and monitored by remote experts.

- In part manufacturing, CNC machines are automated and programmable machine tools used for cutting or moving a piece of material to meet a required specification without a manual operator directly controlling the machining operation [54]. The cobot carries out machine processes and is used by the remote expert and serviceperson carrying out their functions in the mobile application. This actor has the following goals:

  - secondary actor,
  - performs machine processes,
  - can receive and process instructions sent by the remote expert or serviceperson,
  - and can execute tasks given to it.

For the design of this system, use case diagrams were used to give a graphic illustration of the scope and use case of this part manufacturing mobile application. It shows the different functions and actors involved in each use case, as well as how these functions interact. The use cases of this mobile application are remote assistance (Fig. 5), remote maintenance (Fig. 6), collaboration with cobots (Fig. 7), and teleoperation of machines (Fig. 8).

4.4 Design evaluation

Design solutions which include mockups, simulations, and prototypes are necessary to support the design lifecycle, allowing the creation of blueprints of the final product for usability testing. Mockups are visual representations and are also referred to as high-fidelity designs because they translate design concepts into tangible artifacts and include features that allow users and stakeholders to visualize the final product. While mockups may look like the final product, they do not have any navigation, functionality, or interaction. As soon as any navigation or interaction (such as a click or tap on a kebab/hamburger icon to open a navigation menu) is added to a mockup, it becomes a prototype [55].

Prototypes are representations and simulations that demonstrate how a user will interact with a new product or system [56]. Figma is a tool that allows prototyping while design is being done and vice versa. It helps bring ideas to life in animated prototypes which enable testing of concepts earlier and often thereby creating a better blueprint and design for development [57]. In selecting a tool and platform to design this system's prototype, several other design tools and platforms such as Adobe XD, envision, sketch, etc., were looked into but Figma was chosen because compared to these other tools, Figma pays more attention to the products details, was built to strongly foster collaboration and enables cloud storage syncing of files [58].

The design of the prototype of this part manufacturing mobile application is done using Figma because not only does it allow the toggling between design files and live prototype, but it also enables an intuitive build that connects UI elements, and interaction functionalities which allows the defining of subtle interactions like on click, tap, etc., and also mobile viewing which enables the viewer to experience the created designs in real life using the Figma mobile application which is available for iOS and Android devices.

The prototyping of this mobile application using Figma's features allowed the creation of interactive flows that are used to explore how the users may interact with the system design. It was also a fantastic way to preview interactions and user flows, share ideas enabling the collection of feedback from collaborators, and test interactions and experiences of users as well as present the designs to required stakeholders [59].

After an iterative process using formative evaluation methods, the prototype for the on-site worker, remote expert, factory serviceperson, and system interactions was completed. The key design decisions based on user feedback were around the division of tasks and responsibilities of both the human (worker, expert, and serviceperson) and the technology (cobot and monitoring and control systems) aspects. The resulting UI/UX design prototype of the mobile application was divided into three prototypes for the three intended users of the system: the on-site worker, the remote expert, and the serviceperson. An example of the prototype mobile application can be seen in action in Fig. 9—the remote monitoring process for the remote expert for both the CNC machines and cobots is described as follows:

- *Monitor machine/cobot menu:* From the home page as can be seen in Fig. 9, the expert clicks the *Monitor machine* or *Monitor cobot* menu option to opens the remote monitoring page which shows a live video stream of the machine or cobot being monitored.

- *Remote monitoring page via real-time video stream:* Here, the remote expert observes the monitoring page which shows a lifestream of videos of the machine or cobot being monitored. When done with monitoring, he clicks on the *Cancel* button which takes him to the *Status report* page.
- *Remote monitoring page via dashboards:* In the status report page, the remote expert is provided a dashboard view where he can observe and monitor the machine or cobot's status report, the machine logs, and activities in a graphical or tabular representation. When done with monitoring, he clicks on the *back* button and returns to the home page.

The shareable link to the prototype simulation for the on-site worker, remote expert, and serviceperson is given below[1]:

- *On-site worker:* See worker's prototype, to access the on-site worker's prototype simulation.
- *Remote expert:* See expert's prototype, to access the remote expert's prototype.
- *Serviceperson:* See serviceperson's prototype, to access the serviceperson's prototype simulation.

Once this design prototype is implemented, an empirical evaluation can be conducted with actual users to figure out if the system works right. Further, it can also be compared against a normal environment without any of the teleworking components to make sure there are not any unforeseen effects. Factors such as efficiency, effectiveness, usability, user satisfaction, etc. will also be evaluated.

4.5 Outcomes

A system has been developed that simultaneously addresses remote monitoring, remote control, remote assistance, and remote maintenance. Requirements have been derived based on different roles (on-site worker, remote serviceperson, and remote expert), forming the basis for establishing suitable telecollaboration modes. The interative development of the system showed HCD is suitable for design as it fulfills many requirements and allows for project evaluation. The chosen roles are meaningful. In series production and multi-machine operation, for example, the remote expert can monitor several machines simultaneously, thus compensating for the delayed response time and limited monitoring capability resulting from remote access. This allows for an initial diagnosis and is addressed by HCD through the development of a user-friendly interface and the determination of necessary information in advance. Analytical evaluations (expert evaluation and cognitive walkthroughs) have shown potential for this approach, however, they have also highlighted that the roles are not yet complete. They currently only cover experts working remote and traditional workers on-site. An outcome of these evaluations is the need to examine different collaboration roles and application scenarios such as allowing the serviceperson and expert to communicate directly without having to go through the on-site worker. Additionally, the reverse where the expert is on-site and the worker is remote is also important and the resulting potentials need to be also assessed. Another case is that of allowing the remote expert to offer assistance without waiting for the on-site worker to report a problem. For instance, asking the on-site worker to physically inspect a machine's sudden rise in temperature.

An additional related point is to develop an adequate method for task sharing. The individual requirements for specific tasks already form the basis, but further investigations are needed to develop methods for effectively distributing these tasks among different roles, especially for on-site workers and cobots. Automated or simple tasks (such as part insertion or tool changes) can be handled by cobots, while more complex tasks (such as setup tasks like calibrations) require human intervention. Further research is needed to determine whether such tasks must be done on-site or how different roles can help make these tasks partially remote (for example, through remote guidance from experts).

5 Conclusion

Part manufacturing is a key element of industrial production, which relies to a varying degree on human tasks to continuously ensure regular 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 where on-site employees collaborate with teleworking personnel in various constellations. No existing approach addresses this scenario or comprises all technical aspects that are implied with the envisioned collaboration modes. Due to the high complexity and the required quick ramp-up of the collaborations, high usability needs to be the predominant goal during design. The HCD approach which has not been adapted for the described purpose before provides a suitable foundation.

For this reason, various functional and non-functional requirements were derived using the HCD in this work and

[1] This shareable link will only be valid and functional for a maximum of 1 year from the date this paper is submitted.

a conceptual framework was presented as to how teleworking modes must be designed. In doing so, various roles of employees were taken into account and directly considered in the requirements analysis and conceptualization of the design.

The result is a UI/UX interactive design prototype of a system designed from a human-centered design approach that enables various modes of telework collaboration to maintain part manufacturing operations. The initial study presented highlights the development of basic telecollaboration modes, however, to achieve a more comprehensive representation, various alternative configurations will be investigated in the course of further studies. In this way, an independent design of telework modes is to be ensured which can be adapted depending on the application.

Additionally, focus will be on three application scenarios with different automation degrees. A milling machine with manual part handling and tool change, a milling machine with automated tool change and a turning machine with automated part handling by cobots. Specific tasks will be broken down into smaller work elements, analyzed, and then allocated to the various roles and skill levels of workers based on their requirements. This approach will enable a variable distribution of roles that is not only rooted in the roles described earlier but can also be flexibly adapted according to the available personnel.

6 Supplementary information

As part of the supplementary information, shareable links to the walkthroughs of the prototype for the one-site worker, remote expert, and serviceperson are provided.

Appendix A

Functional and non-functional requirements

Please refer to the tables for functional (Table 1) and non-functional requirements (Table 2).

Table 1 Functional requirements

Function	Statement	Function summary
FR-01	Login	User must have a valid username/email and password to use this system
FR-02	Real-time communication	The software will allow real-time communication between a remote expert and on-site worker. The expert will guide the on-site worker. Both can communicate via audio or video call
FR-03	Integrated chat function	This function eliminates the need to use third-party programs in a different window or another device to connect with aid seekers and helpers
FR-04	Record the session of communication	In this case, if the problem reoccurs, the person seeking help will immediately have personalized video instructions to solve the problem on their own
FR-05	Collaboration via Augmented Reality (AR) wearables	Remote experts, servicemen, and on-site workers can merge their environments using remote assistance technology, allowing collaboration to take place from anywhere. This implies that an expert can be virtually present to instruct on-site workers on essential tasks via AR and VR devices such as AR glasses
FR-06	Real-time transfer of information	It is extremely useful to share actionable information in real-time with team members, experts, and coworkers. Remote virtual assistance can be used to share a wide range of data. Users can combine their videos and work together in a virtual setting to review and act on information
FR-07	Information gathering	There is a recording feature incorporated. Information gathering and delivery, access to documentation, and knowledge management are all possible and can also be done with the use of AR glasses
FR-08	Equipment installation	Engineers can use remote virtual assistance software to remotely assist workers through the installation process using their expertise. They can give precise directions and, if necessary, call in more experts. Support is available in real-time, assisting in the appropriate installation of equipment. This is true even if the worker doing the hands-on work is unfamiliar with the installation process
FR-09	Equipment Service	Servicemen and equipment engineers can use remote virtual assistance software to remotely assist workers through the installation process using their expertise. They can give precise directions and, if necessary, call in more experts. Support is available in real-time, assisting in the appropriate installation of equipment. This is true even if the worker doing the hands-on work is unfamiliar with the installation process
FR-10	Quality assurance inspection	This software will allow for quality assurance inspection and ensure that quality requirements will be fulfilled. It also involves Quality Control, which ensures that the machine processes run smoothly. Remote assistance allows inspection of the machines and processes for quick and efficient quality control. To inspect operations, quality specialists can be virtually present. This speeds up problem resolution by facilitating inspection cooperation and the capacity to remotely discover manufacturing flaws and errors
FR-11	Remote maintenance	Maintenance is a compulsory aspect in any industry. Remote maintenance allows the workers to communicate with the relevant factory servicemen on video or audio sharing to resolve issues with equipment. Factory servicemen provide their expertise to routinely maintain or solve the issues with equipment

Table 1 (continued)

Function	Statement	Function summary
FR-11 A	Request remote maintenance	This software will provide a request module for maintenance. The on-site worker or the remote expert manually requests for maintenance of the machines when a potential error is observed
FR-11 B	Provide remote maintenance	The remote experts will provide guidance and help to resolve the problem that is indicated in the request
FR-12	Teleoperation of cobots	Cobots is an effective way for part manufacturing employers to address these reduced workforce issues. It enables the companies to increase productivity, and turnover and improve quality, despite any ongoing labor market shortfalls. These cobots will controlled by the remote experts to collaborate and assist the on-site workers with physical tasks
FR-13	Remote monitor and control of cobots	Humans could find it monotonous to complete tasks, in the same manner, day after day, whereas cobots could do this efficiently with complete consistency. Humans could find it monotonous to complete tasks, in the same manner, day after day, whereas cobots could do this efficiently with complete consistency. When there are operations that require a high level of precision and repetition, cobots would be used to perform these tasks. Since Cobots are already designed for performing collaborative tasks. The system will provide compatibility with the cobots, so remote experts will be able to monitor and control the cobots remotely. The Cobots will have an attached camera to send live feeds of activities being performed
FR-13A	Remotely control cobots to monitor machines	The system has a feature to closely monitor machines either when required by the expert or when the expert is guiding the on-site worker and needs the cobots to just closely monitor the machine being worked on and provide a very close feed of the work environment. Remote experts will control the cobots to perform routine, repetitive, and dangerous tasks
FR-14	Collaboration with machines	Given that the machines are CNC and can perform tasks as per given instructions. This system will provide a module to remotely monitor and control the operations of machines. Remote experts and servicemen can monitor the machine to check its performance and quality. Also, they can control the machines remotely
FR-15	Remote control of machines	While this software will not directly control the machines, it will be embedded or linked to the software of the CNC machine, and it will then be used to give it instructions and control it from a remote location. It will also ensure real-time transfer of data and instructions and ensure low latency between the CNC machines and the software being built
FR-15A	Remote monitor of machines	The system will ensure remote monitoring of the CNC machines using surveillance devices strategically placed on-site at the location of the machines. These surveillance cameras should also ensure real-time transfer of video feeds

Table 2 Non-functional requirements

Function	Statement	Function summary
NFR-00	Safety	It must be ensured that the system is always safe and that its use does not pose a risk to employees or the environment
NFR-01	Availability	We should aim to ensure the system is available to users 99% of the time. When the expert receives a request for assistance and maintenance, the system processes this instantly when received at any time. In instances where the system is down a process should be in place to queue requests and assist them once the system is back up
NFR-02	Backup schedule	Backing up is an important part of ensuring a reliable system. The system should be capable of performing backups. Full backups should be completed at least once a month. Incremental backups should be completed at least once a fortnight with the same settings and differential backups should be completed daily
NFR-03	Fast interoperability	For all external systems that the system interfaces with, interoperation should be quick, accurate, and seamless. Ideally, any information required should be processed instantly for both parties. All information transferred between systems should be accurate and re-transmission should occur in case of any failure. Communication between systems should take place in a way that causes minimal to no obstruction to users using the system
NFR-04	Remote processing time	Remote processing times should ideally be within 400-500ms. Remote users should be able to process updates to notes, scheduling, or any other important functions swiftly over the system. The system should be able to provide this level of performance to all users who work remotely
NFR-05	Usability	The user interface of the system should be very simply designed and easy to follow. On-screen help prompts should be available for users who are struggling with how to complete certain operations. The interface should adjust for the various disciplines and intuitively add/remove form input fields and options that are not relevant to the specific user
NFR-06	Reliability	The system should work without failure as close to as much of the time as possible, which we will quantify as 99% of the time. All operations processed through the system should be done correctly. For any errors with updating data, the system should immediately roll back any changes and prompt the user who prompted the error to retry the operation. Any bugs found in the system that interfere with operation should be ironed out as soon as found

Table 2 (continued)

Function	Statement	Function summary
NFR-07	Maintainability	If maintenance is required for any reason on the system, individual functions should be able to be isolated. The system should be modular, and these modules should be isolatable from each other. The system should be designed to accommodate regular maintenance and provisions should be in place to minimize the impact that this maintenance has on parts of the system that do not require maintenance
NFR-08	Scalability	The system should have provision to support three to four times the number of current users and handle three to four times the current volume of data in the future while providing the same performance measures as currently. The system should also be able to accommodate the addition of further functions not currently required for its organizational purposes
NFR-09	Low latency	Low latency is a key feature because this system provides remote assistance, maintenance, and real-time collaboration so, it has to be efficient in terms of time. In addition to the remote processing time mentioned above, the processing time must be minimal during the transfer of information. The delay before a transfer of data begins following an instruction for its transfer must be at the lowest, with the maximum time being 1 s. The surveillance cameras, that will monitor CNC machines, should also ensure the real-time transfer of video feeds
NFR-10	High responsivity	The system must be able to respond quickly. Request for remote assistance and maintenance must be transferred in real-time so the issue will be solved immediately
NFR-11	Compatibility	Since this system is to inter-operate with CNC machines and cobots, the software system must be compatible with both. The system must be compatible with the CNC machine software to remote control the machines. Cobots will also be remotely controlled by the remote experts and used for collaboration, so compatibility must be ensured

Appendix B

Mobile app use cases and workflow

See Figs. 5, 6, 7, 8, and 9.

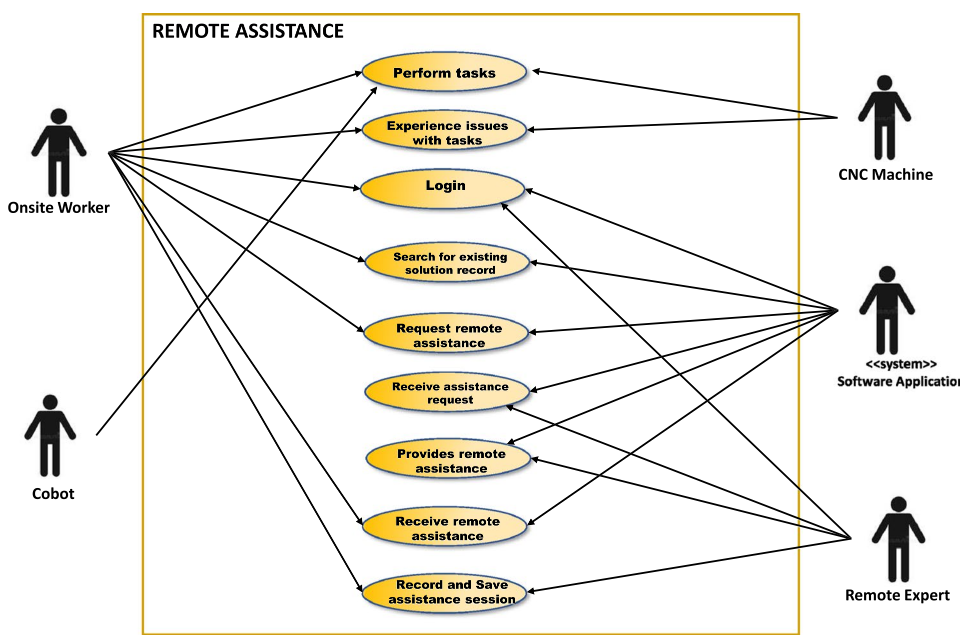

Fig. 5 Remote assistance use case diagram

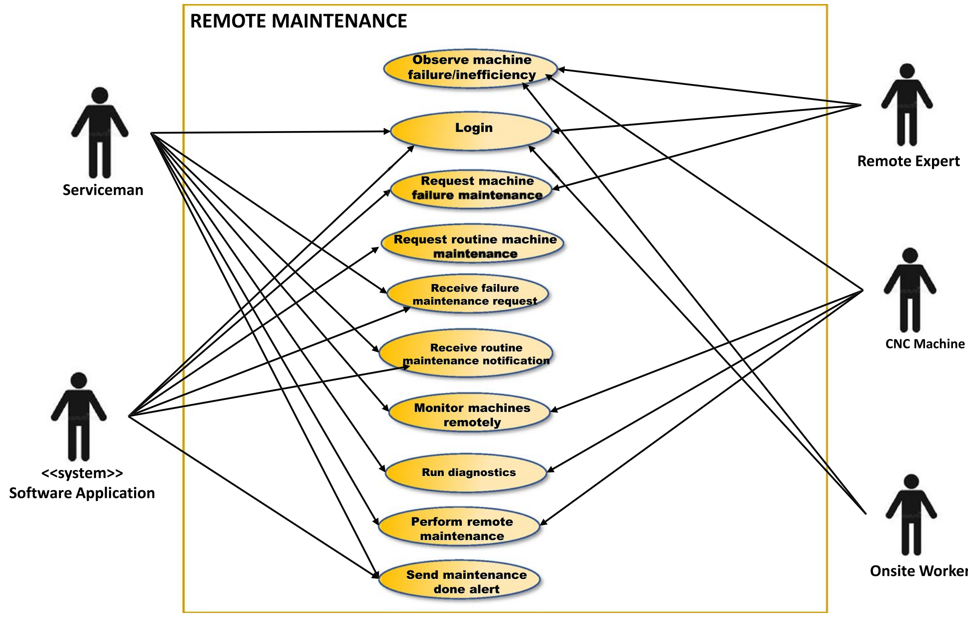

Fig. 6 Remote maintenance use case diagram

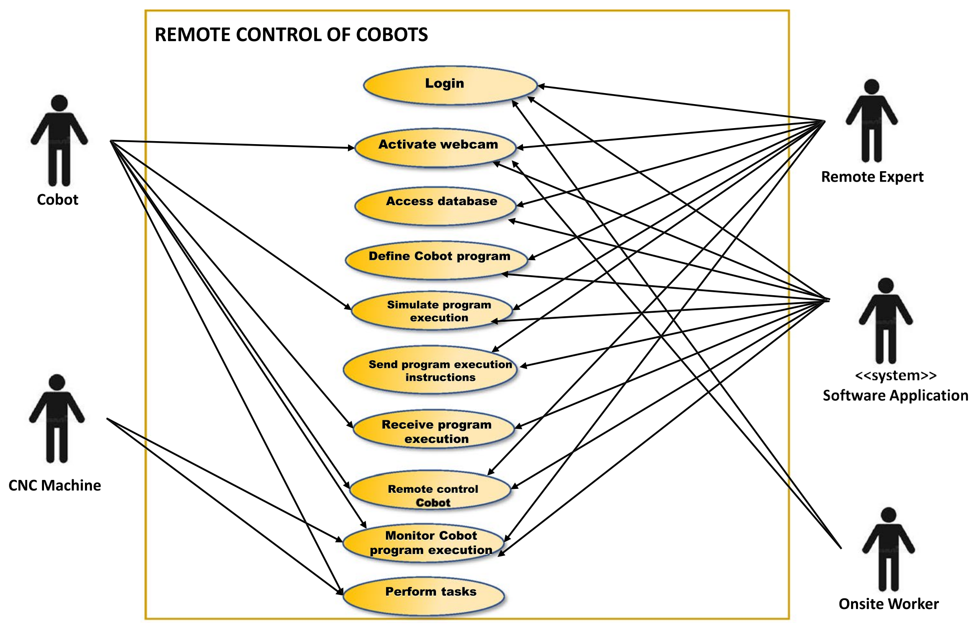

Fig. 7 Remote control of cobot use case diagram

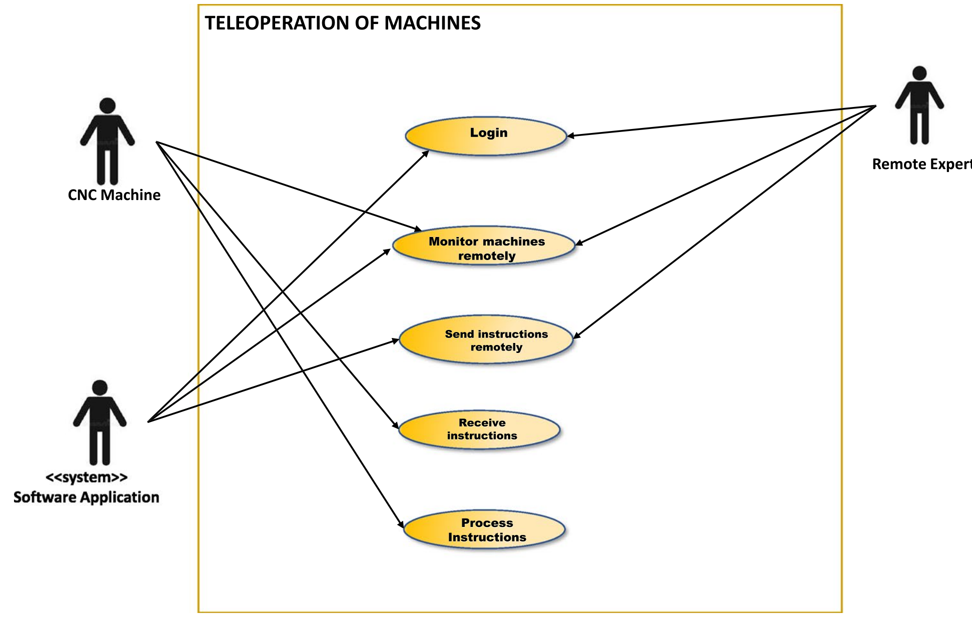

Fig. 8 Teleoperation of machines use case diagram

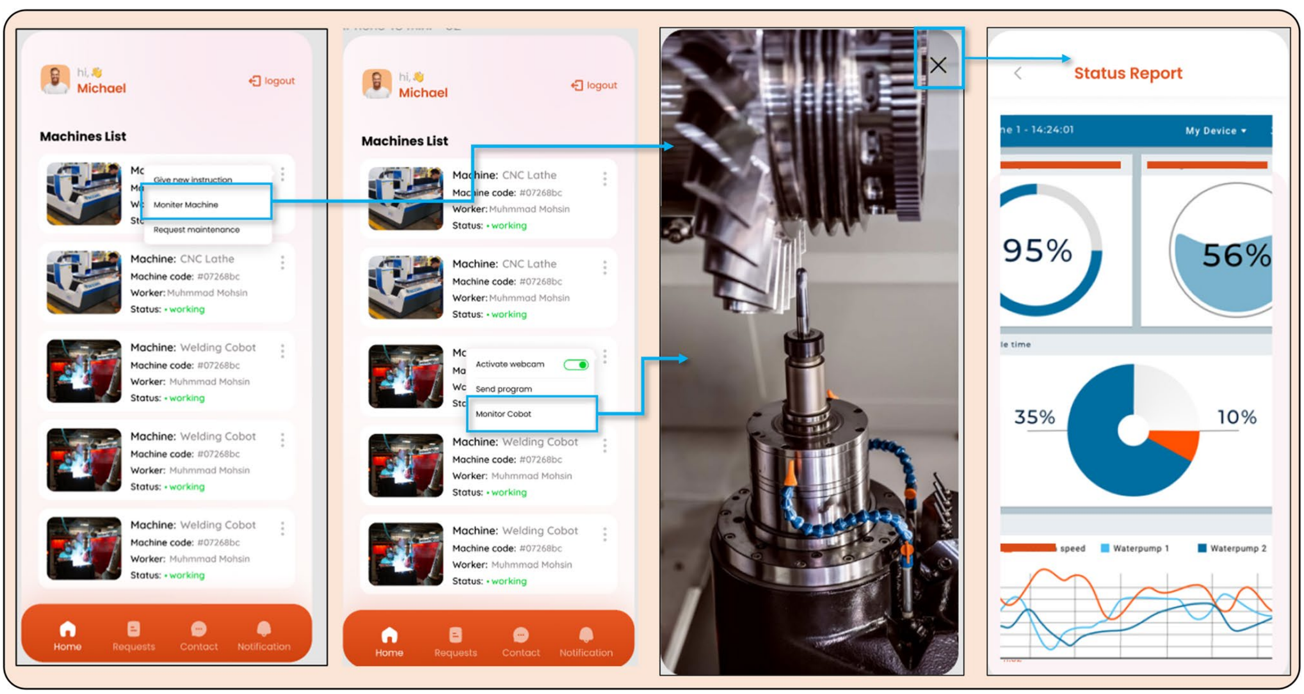

Fig. 9 Remote expert's remote monitoring page

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Declarations

Conflict of interest All authors declare that they have no conflicts of interest.

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