Development and Evaluation of an Assistive Workstation for Cloud Manufacturing in an Ageing Society

T. Linner[1], J. Güttler, C. Georgoulas, A. Zirk, E. Schulze[2], T. Bock

Abstract

The elderly can be considered as an important labour force for future industrial development in Germany, in particular in the context of design and production of value-added, personalized products/services that demand skilled and experienced labour. In this context, the project USA² developed, classified, and evaluated scenarios for the utilization of Cloud Manufacturing technologies and developed and prototyped an exemplar future assistive workstation for the elderly allowing them to produce personalized products decentrally and close to the customer. This article outlines the methodological approach of the project and the prototyped key subsystems and discusses relevant aspects of development and evaluation.

1. Background, Research Question & Method

By 2030 there will be approximately 7 million fewer workers than today in Germany, resulting not only in a reduction of GDP by around 16% [1], but (in cobination with unchanging structures and strategies of the services and manufacturing industries) also in a huge loss of knowledge as the workers carrying the knowledge enter into retirement. The first large-scale studies conducted for example in connection with Japan's "Silver Human Resources Centers", show that social participation, quality of life, and mental and physical health of ageing workers and elderly can be positively influenced by the assignment of coordinated, meaningful work tasks [2]. In the future, the ageing of our society will lead to a growing number of elderly. In combination with improved health [3, 4] and a continous increase in life expectancy [5, 6], the elderly could be considered as a huge labour force important for the future industrial development in Germany, in particular in the context of the design and production of high-value-added, personalized products and services that demand skilled and experienced labour. Assistive workstations (Fig. 1), as presented in this article follow a consequent, technical approach for assisting in the working environment and can utilize the potential labour force of the elderly through applying Ambient Assisted Living (AAL) approaches. AAL approaches have so far been

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used mainly to create assistive furniture [7], assistive mobility systems [8], and assistive home environments [9, 10]) and their application to work environments is a novel research topic.

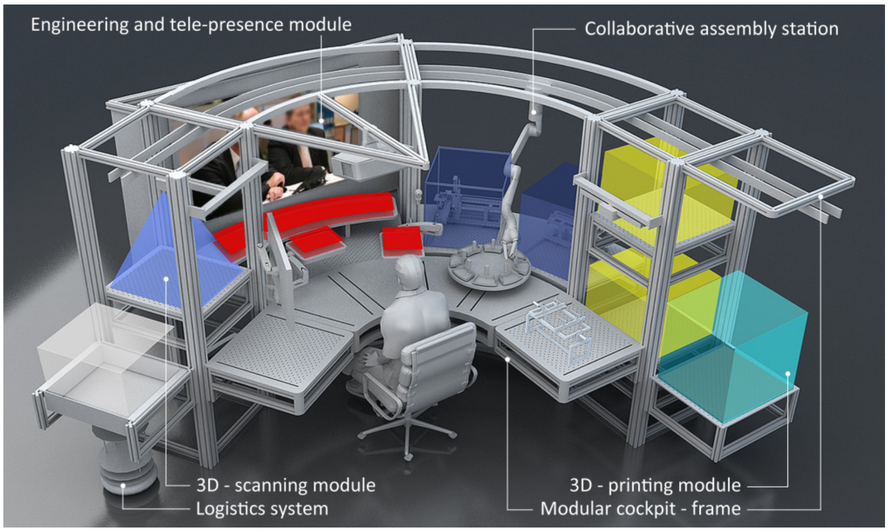


Fig. 1: Overview of the assistive CM workstation and its key functional modules.

Fig. 2: Elderly person producing a personalised product by a collaborative robot system that is informatically and kinematically integrated with the workstation.

The idea of assistive workstations can be connected to a new structural and technological concept: Cloud Manufacturing (CM; [11-15]). Since the mid-1980s, this new concept has been worked on in research laboratories around the world and it includes ICT-based manufacturing technologies such as Desktop Production, Desktop Assembly, 3D-scanning, Collaborative Robots, Collaborative Working, Telepresence and autonomous Mini-factories. The development of concepts for decentralized production, as well as the rapid development of fields such as Computer

Integrated Manufacturing and Collaborative Design provide complementary ICT-based innovations that enable the connection of a large number of physically distributed entities to value or manufacturing networks in the sense of CM. The integration of these new technologies in the living environment can be done in a way that takes into account socio-technical and psychological aspects and thus is able to positively influence aspects as social participation, mental and physical activity (see for example Fig. 2 showing and elderly person producing a personalized product in the proposed assistive workstation), individual feeling of worth, and the individual life and health situations [16].

In order to develop, classify and evaluate possibilities and scenarios where technologies from the area of CM could be used for assistive work environments for the elderly, the authors set up the BMBF-funded, experimentation-focused project USA² (German: Ubiquitäres und selbsständiges Arbeiten in einer alternden Gesellschaft / English: Ubiquitous and independent working in in an ageing society, BMBF grant number: 16SV6191; duration: June 2013- October 2015). The research project followed an experimental, iterative approach. Very early in the project, users (usability test 1; chapter 4) as well as stakeholders (workshop; chapter 5) were involved through systematic scientific survey methods. On the basis of the specified approaches, requirements and functions (chapter 2), the assistive workstation was implemented as a fully functional cockpit-like mock-up and was optimized in several iterations in terms of workflow, ergonomics, and assistive functions (chapter 3). As a result, the assistive workstation was designed on the basis of a modular concept specifically developed for the project (modular frame, modular functional infill, etc.) which allows for further modification/optimization and adaptation to a variety of alternative application scenarios. The discussion with users and stakeholders continued throughout the project and led to the exemplary realization of some sub-systems (chapter 3) as well as the design of some industry-oriented application scenarios (chapter 5). In a second usability test (usability test 2; chapter 4), the system was finally tested with 20 test persons using a systematic combination of different evaluation tools (including the System Usability Scale, SUS, and the NASA Task Load Index, NASA TLX) in terms of usability and the need for further research and development (chapter 4). The mock up of the assistive workstation allowed for the production of a simple personalized product, and the test persons were guided through the associated work procedures.

2. Conceptual Approach, Requirements and Sub-Systems

The utilization of the above-mentioned technological possibilities allows for the use of knowledge, the life experiences and the labour market potential of the elderly throughout the entire life cycle of the generation of high-value-added, personalized products. Additionally, concepts and software systems from the area of Computer Integrated Manufacturing (CIM, in development since the 1990s, see for example [17]) and fom the area of Product Information Modelling (for example [18]) can help to integrate various locally, and in terms of time separated value added steps, as well as massively distributed workplaces, work environments and workstations (as proposed in this article) to virtually integrated value creation networks. Accordingly, four use cases and the associated functional requirements were formulated (Fig. 3) from which then sub-systems/modules and processes were derived (Fig. 4).

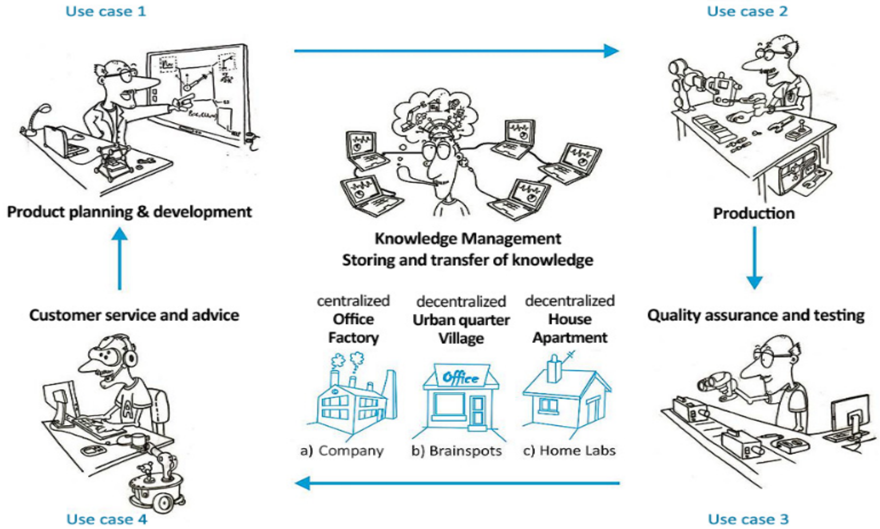


Fig. 3: Structural design of the examined scenarios according to the product life-cycle model (definition of functional requirements)

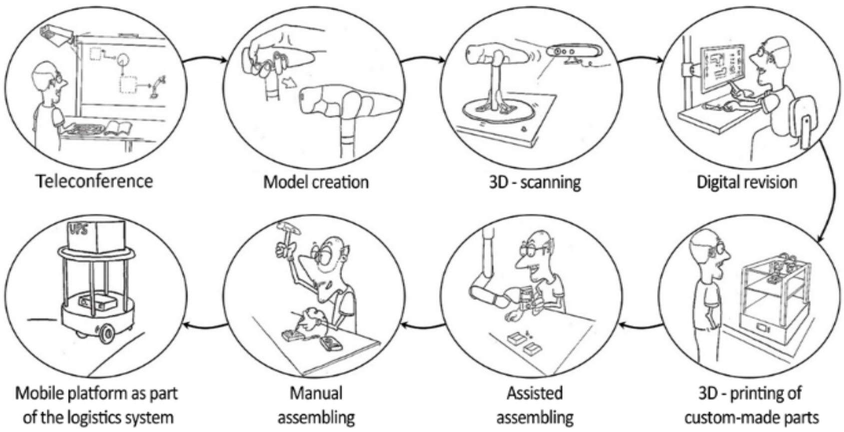


Fig. 4: Overview over the implemented modules and their interaction with each other and the user (definition of concrete functional modules and processes)

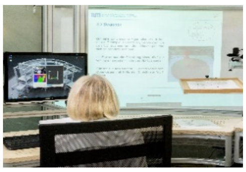
In order to ensure that the assistive workstation can be operated decentrally, and thus close to the customer in the sense of CM for the adaptation/personalisation of products by the elderly users of the worstation, all functional requirements throughout all four use cases (product planning and development, production, quality assurance and testing, customer service and advice) have to be considered and integrated as basic functions into the workstation in a compact way (for more information on the necessity of integration of value added steps in service-driven markets see also [19, 20]). Depending on the specific application scenario for the production of a distinct personalized product, the workstation proposed in this article can then easily be adapted (see also Fig. 8 as an example; for further information on demands of the stakeholders, see chapter 5). Furthermore, in the sense of CM, not all parts or components required for the personalized product must be designed or produced via the workstation by the elderly but they can be (in a network of economic entities) provided by other CM workstations or even by a central supply entity or factory providing basic components or raw products.

3. System Architecture and Sub-systems

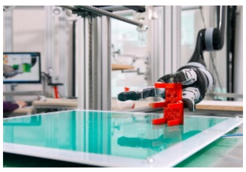
Modular cockpit-frame: The assistive workstation was developed following the example of an airplane cockpit in order to transfer the ergonomic strategies from innovative cockpit design (reachability, flexibility, adaptability, etc.) into work environment/workstation design. The main frame (utilizing custom-made MayTec profiles) was designed on the basis of a specially designed, novel modular grid system, allowing the implementation of the cockpit analogy. The workstation allows for flexible adaptation towards various application scenarios.

Logistics system: The key element of the logistics system is a mobile platform, which is in this project exemplarily symbolized by a TurtleBot. It is able to carry parts or products to or away from the workstation. The TurtleBot is based on the open source software ROS [21]. To enable it to be a key element of the logistics system, a novel system architecture was implemented [22]. This system architecture allows various control modes (for example Leap Motion controller, microphone, etc.; see also Fig. 7) to be used in combination with a ROS-based Master (Tablet) PC to control the TurtleBot.

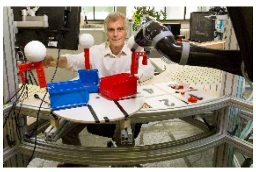
3D-scanning module: The 3D-Scanning module offers an easy and fast way to generate very complex and highly customized CAD models (for example, a hand, finger, arm or ear – or a cast / imprint of those - for a person requiring a product that must be adapted or personalised). In the workstation, two systems are embedded: a) a depth camera for objects lager than 80 cm and up to 3.5 m. Here, a 360° rotation is already enough to achieve a strong result; b) a laser-scanner system, which is able to measure objects that are too small for the depth camera.



Engineering and tele-presence module: In order to enable the user to attend meetings and collaborate on tasks concerning distant persons, a telepresence module was implemented in the workstation. Due to the size of the screen, people in distant locations appear life size in order to make communication as natural and efficient as possible. Furthermore, this module supports the social interaction between the user and other producers or experts, which can also be equipped with a CM workstation.



3D-printing module: 3D-printing offers a cheap posssibility to produce custom-made parts for personalized products. The raw material polylactide (PLA) used for printing is biocompatible and therefore several use cases for the production are possible (e.g. bracer productions etc.). The 3D-printer is implemented on the very right side of the workstation, where The Jaco Robotic Arm (JRA) also has access in order to grasp ready printed parts out of the 3D-printer and carry them to the collaborative assembly station.



Collaborative assembly station: At the collaborative assembly station, the user is assisted by a JRA. In order to test how the elderly users would cope with various human-system interaction concepts, three different control modes (half-automatic, manual, gestures) were implemented and tested (Fig. 6). For the gesture based control mode, the Leap Motion Controller has been used [23]. In order to link the Leap Motion Controller to the JRA, it was necessary to develop an algorithm to translate the Cartesian coordination system of the leap motion sensor to the JRA.

Above the overall system architecture of the assistive workstation (modular cockpit frame) and the functional and technical details of key sub-systems (because they are potentially exchangeable and adaptable to a specific application scenario, they are also called “modules”) are depicted. So far, five key functional modules have been prototyped and integrated into a modular cockpit-like frame serving as a kind of product platform: (1) logistics system, (2) 3D-scanning mdule, (3) engeneering and tele-presence module, (4) 3D-printing module and (5) collaborative assembly station. These key modules allowed the simulation of work flows within the workstation, as for example the personalization of hearing aids, walking sticks and rollator/wheelchair handles towards person-specific physiological and ergonomic requirements.

4. User Integration: Evaluation and Usability

In order to tailor the workstation to the needs of the target group (older workers and elderly people) the assistive CM workstation was prototyped with all its functions. Two laboratory-grade tests with real test persons were conducted. The laboratory-grade tests were conducted in the construction robotics experimentation lab at Technische Universität München, where the workstation was prototyped and thus, a real world assembly scenario was simulated. Usability test 1 was conducted in the first half of the project (7 test persons/N=7; focus was more on open questions, behavioural analysis as well as scenario and functional modules improvement), and usability test 2 (21 test persons/N=21; focus assembly scenario, structured questions and usability evaluation of various human-system interaction/control modes) in the final phase of the project. The outcomes of the systematic evaluation conducted within each test were subsequently used to improve the system. In the following section, the key outcomes of usability test 2 are summarized. In cooperation with the Berliner Institut für Sozialforschung GmbH (English: Berlin Institute for Social Research) and the development team at Technische Universität München, a second usability test was conducted. A key element of this test was not only the evaluation of the individual functions of the workstation itself and the work procedures but also the evaluation of different control modes (for example semi-automatic, manual, gestures, voice, etc.) which were developed throughout the course of the project aiming at older workers and elderly people. 21 test persons (aged 60 +) with predominantly engineering / technical backgrounds took part in the usability study. During the testing they were asked to conduct tasks in the production of a simple, personalized product (3D scan, work on a product model and 3D-print parts, assembly of product using the JRA in the collaborative assembly station, use of the logistics systems). The usability study was carried out using quantitative and qualitative methods and a combination of (1) SUS-based evaluation, (2) NASA TLX, (3) a questionnaire using a Likert scale and a (4) guideline based interview with the test persons. To characterize the test persons, questionnaires to analyse their affinity with technology (TA-EG, questionnaire on technological affinity related to electronic devices), technology usage and demographic data were combined. Overall it can be said that the test persons, on average, showed a strong acceptance of technology and an affinity for technology. In addition, they felt competent in dealing with technology and even consider themselves partly to be technology enthusiastic.

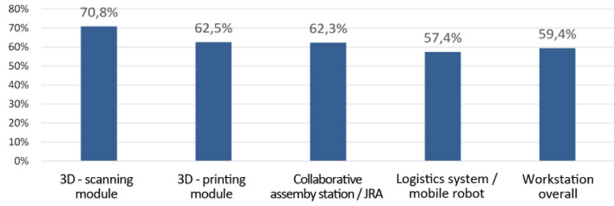
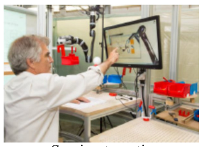


Fig. 5: Average SUS scores (M) for the functional modules and the workstation; N=21.

Collaborative Assembly:



Semi-automatic

Manual

Gesture

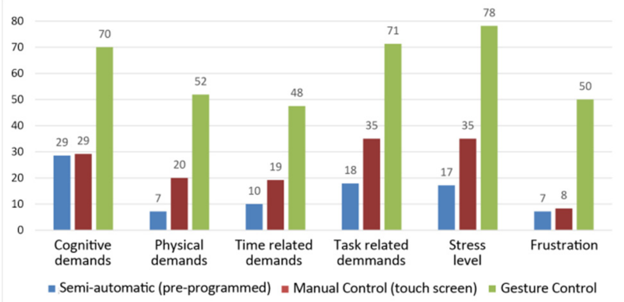


Fig. 6: NASA TLX: average perceived task load levels (M) for test persons when operating the JRA in the collaborative assembly station by various, alternative control modes; N=21.

Logistics System:

Semi-automatic

Manual

Gestures/Voice

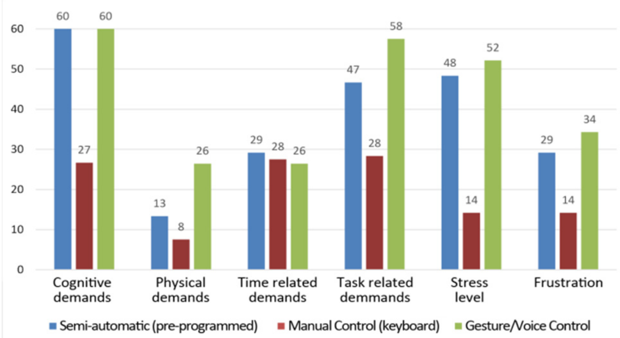


Fig. 7: NASA TLX: average perceived task load levels (M) for test persons when operating the mobile robot beeing part the logistics system by various, alternative control modes; N=21.

The SUS evaluation (Fig. 5) shows a slight variation between the scores achieved by the individual functional modules. With a score of M = 70.8, the 3D scanner performed best and can be considered to have good usability. The JRA that is part of the collaborative assembly station achieved a usability score of M = 62.3. It should be noted, however, that in the case of the JRA, the ratings between the different control modes (similar as in the case of the mobile robot that is part of the logistics system) varied considerably and this rather poor performance was a result of the averaging of extreme values. The usability evaluated by the SUS correlated with the NASA TLX values that were determined for the perceived work loads. Fig.

6, which shows the NASA TLX values for the different control modes of the JRA, indicates that the relatively low usability of the JRA as part of the collaborative assembly station is caused, in particular, by the percieved, extremely high levels of task loads during the gesture control (M = 70). This helps to explain the overall perception that relatively high levels of effort were required by the test persons for controlling the JRA compared to the other functional modules. Fig. 7 shows that for the mobile robot, the perceived average SUS scores and NASA TLX values were also an outcome of the averaging of the preceived task load levels of the different control modes. The NASA TLX was also used to determine the percieved task load levels for all other assistive workstation modules and associated control modes.

5. Stakeholder Integration: Application Scenarios

With the aid of assistive, decentralized working environments/workstations for older workers and elderly people as described in this article, companies are potentially able to produce personalized products within mass customization and product personalisation strategies (for more information on this, see for example [24]). Another advantage of decentralized production is the speed at which new product types can be developed, designed, produced and delivered. CM in combination with the assistive workstation presented in this article is able to give industries the possibility of responding in a near real-time manner to market changes (on the possibilities of the real-time economy in the context of distributed mini-factories, see [25]). Based on these propositions, a workshop with stakeholders (N=10; technology suppliers, manufacturers of work environment systems, potential appliers of the workstation) was conducted. Various scenarios and the question when and how the proposed workstation can be used to enable older workers and the elderly to participate in employment from home were discussed with the stakeholders.

Table 1: For Cloud Manufacturing suitable product fields

In accordance with SFB 582:	**According to project research:**
• High-quality household appliances with high frequency of use by users • Lifestyle products with emotional character (watches, mobile telephones, sportscars etc.) • Medical devices (e.g. hearing aids, prosthetics, etc.) • Sport, fitness und free-time devices	• Custom furniture • Home Care & Ambient Assisted Living • Robots (service and lightweight robot), custom tools and moulds • Automotive industry (particularly in the area of suppliers to 2/3 tier level) • Custom controls and user interfaces, rehabilitation technology • Microelectronics (small series) • Custom sensors • Custom circuits, ICs, motherboards, etc. • Safety systems • Product disassembly und Product re-use / re-cycling and re-manufacturing
According to Germany's high-tech strategy: • Bio-labs • Nano-labs	

Based on this, the following issues were identified as being relevant: a) What types of career fields may be affected? b) How does the home workstation need to be conceptually designed? c) With what functional modules/technologies must a home workstation be equipped? Furthermore, it was found, that the requirements to be met by the workstation are determined by the individual "setting" (specific scenario or industrial/home environment for which the workstation is used) and also by the needs of the users (elderly). It was concluded that the workstation must be capable of being adapted towards individual needs of the economic entities, stakeholders, and elderly using it. Furthermore, relevant application fields were defined (Table 1). From these application fields, some products were selected as examples and the associated scenario settings were developed and simulated (Fig. 8).

1: Station for capturing of physiology of customer; 2: Station for customer data analysis and product planning; 3: 3D-printer; 4: Injection molding machine; 5: Assembly station; 6: Quality testing station; 7: Assembly guidance system; 8: Packaging station

Fig. 8: Setting for the design and production of personalized automotive equipment (in this case a personalized steering wheel)

6. Conclusion and Further Development

In the research presented, a solution space was explored for the development of assistive CM workstations geared towards the elderly for the development/production of value added, personalized products and services Application scenarios were detailed and discussed with users and stakeholders. A fully functioning prototype of the assistive workstation and key functional modules were built and evaluated with 21 test persons using a combination of evaluation tools. It can be concluded, that under certain conditions, the application of the assistive workstations (even in a home environment) appears to be plausible and applicable for both users and stakeholders. Elderly are capable of making use of the technological possibilities offered. However, it was also shown that the success of an assistive workstation depends, in particular, on the design and robustness of the human-system interaction. The discussions with stakeholders revealed that processes and organisational structures must be adapted towards this novel approach. Finally, the research conducted showed that the proposed assistive workstation has potential not only for the elderly or older highly skilled workers, but also in general for people with impairments, single parents, nursing relatives and people with restricted mobility. Furthermore assistive work stations can be considered to have potential for the manufacturing industry and in particular in the field of highly-flexible human-centered assembly in which humans and robots are required to work closely together.

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