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A Human-Centered Assembly Workplace For Industry: Challenges and Lessons Learned

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Abstract

The increasing complexity of adapting established assembly processes to fast changing market demands is challenging European industry. Especially for highly individual products the automation of each assembly step is not feasible for both technical and economic reasons. Humans and machines have to work cooperatively in future factories. Like new programming methods for machines, human workers have to be trained for such changed situations. Therefore, this paper presents challenges and lessons learned from a 4-year research project dealing with the reduction of training effort for assembly processes by researching easily configurable, digital assistive systems. These digital assistive systems arranged on a novel 'human centered workplace' range from product-specific work instructions shown on a display and augmented reality solutions for training to collaborative robots. The overall architecture comprises a fully integrated software eco-system for engineering and operating assistive systems, a prototypical assembly station as well as a corresponding transformation process.

Keywords: assistive systems; assembly work; object recognition; smart production; assembly systems 4.0

1. Introduction

Industry 4.0 defines a trend away from mass production towards mass customization. Products are getting increasingly complex and personalized. A wider variety of products means significant changes for people doing manual assembly tasks and increases the complexity of those tasks. New mechanisms are needed to support the required flexibility [4], including novel types of visualizations, interactions, vision-based approaches and collaborative robots. Human-centered assistive systems support workers in completing their tasks by providing step-by-step working instructions. Such assistive systems can potentially provide a variety of different opportunities for manufacturing, such as training employees with less experience, quality assurance, reducing the memory load, and integrating people with impairments into the workplace [4]. With the advances in hardware and software capabilities, more and more op-

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portunities for (industrial) assistive systems arise. To provide optimal support, however, these systems need to be context-sensitive regarding the current state of the product and what kind of information is currently needed by the worker. Combined with the idea of mass customization and the high variant diversity mentioned above, this implies high requirements regarding contextualization and visualization of assembly information. The aim of this paper is to provide a better understanding of the strengths and limitations of different assistive technologies used to support manual assembly tasks with respect to their practical implementation in companies. We still see obstacles with the adaptability of step-by-step instructions (and the rising complexity of workflow modeling depending on the granularity of work steps) and uncertainties in vision-based approaches. Nevertheless, as technology evolves, assistive systems will get more reliable and will play an essential role in smart production environments.

This paper describes the challenges and lessons learned from a 4-year research project with a focus on the creation of a human-centered and configurable assembly workplace for industry. In section 2 we present related work in the respective field with focus on human-centered workplace design. In section 3 we describe the overall concept of our research approach, and subsequently present each part in the sections 4 and 5. Based on our research results, we discuss the overall findings in section 6 and conclude our paper with possible future research.

2. Related Work

Creating working instructions to assist operators in handling complex tasks has been topic of various research projects. For our research, we particularly looked into relevant research projects, which focus on assembly assistance and human-centered workplace design.

Human-centered design — In order to successfully orchestrate assistive systems for manual assembly scenarios, we strive to gain a deep understanding of the needs of manual assembly workers in their everyday environment. Thus we need a better understanding of their real needs and identify contextual influences to design effective, efficient and accepted systems. In our approach, we follow the Contextual Design (CD) methodology described by [2] and later revised in [14] and [13]. CD describes a framework for planning and implementing a human-centered design process throughout all phases of a project typically including the iterative phases (i) *observation*, (ii) *idea generation*, (iii) *prototyping* and (iv) *testing and evolution*. The recommended research method to inquire users in their natural environment are *Contextual Inquiries* (CIs) [15]. CIs are semi-structured interviews accompanied with an observation of the users' everyday work tasks in their own environments. Building on the CIs, we used *Contextual Analysis* (CA) methods to process, organize, consolidate and interpret the gathered user activity data from the CIs. This approach helps to gain an in-depth understand of work practices and context. A detail description of our contextual design process and experiences with lessons learned can be found in [1]. Our in-depth findings for the context of manual assembly and an additional methodology for analyzing crosscutting context types are described in [22].

Assistive technologies — Funk et al. [9] have built a system called Teach Me How!, where in-situ projection is used for interactive assembly instructions. The system highlights the position where a part should be assembled and checks if it is assembled correctly. Their work goes beyond projecting work instructions and it provides very helpful features like pick detection, assembly detection and detection of tool usage. Blattgerste et al. [3] built a system for in-situ instructions. They based their work on the idea of Funk et al. [9] of using 32 instructions on paper for building a specific item with Lego. The Microsoft HoloLens as a mixed reality device or smart glass was used in one of the use-cases as an in-situ assistance. They experimented with a smartphone in a second use-case as another system for mixed reality. To validate, which of the systems is best suited for assistance, they applied the general assembly task model (GATM) introduced by Funk. One of the key measures was the Task Completion Times according to the GATM. In all four phases (locate, pick, locate_pos and assemble) was the paper instruction better than any other mixed reality system like the Microsoft HoloLens and a smartphone. Wögerer et al. [30] have developed a system for industrial assistances. The goal of the project was to implement modular, reusable assistance systems for employees in production companies. Their use cases cover maintenance and service, arming of machines and simultaneous handling of multiple machines, and assembly. Augmented Reality (AR) technology is supposed to have high potential as assistive technology in the process of industrial manufacturing lead to innovative and complex fields of application in the context of Industry 4.0, from intelligent machines, intelligent data management to holistically intelligent factories. The users see themselves at the central interactive interface between computer-aided planning and machine manufacturing through intelligent and networked systems in the sense of the Internet of Things and the industrialized Internet [23].

AR-based assistive systems are not only highly relevant for production in the sense of Industry 4.0 in terms of design and actual production, but are also increasingly of central importance as learning and training systems in the increasingly complex manufacturing processes and the demanding training of skilled workers [27]. As an assistance system, the visual augmentation of reality can use the representation and processing of multi-modal and multi-dimensional data for the human observer. This includes the display of text, the display of images and videos as separate information units or as an overlay of the natural view. In addition to the augmented information provided, the intuitive and natural interaction with the system is of central importance. For the support of industrial manufacturing processes it is essential that the manual activity is not restricted by a controller. Natural control elements for human-machine interaction include special data gloves with the possibility of haptic feedback [28]. Non-contact controls (important in the context of industrial production) using gesture recognition (poses, hands and head) or the sending of control commands by gestures can also be used [20, 6]. Several interaction possibilities were investigated, for example, Microsoft Kinect [25], Myo bracelet [11] and spatial augmented reality systems [16].

Workflow Modeling — In many domains, various modeling languages exist to simplify the implementation and execution process of production systems. For example, the Unified Modeling Language (UML) presented in [26] or the Business Process Model and Notation (BPMN) [10] help users to specify workflows that should be executed. Dumas et al. used UML activity diagrams to specify workflows in an abstract and user-oriented way [7]. Zor et al. extended BPMN for the specific usage of this modeling language in the manufacturing domain [32]. Keddis et al. presented ways to model production workflows in the era of mass customization and introduced a metamodel for these workflows [17]. We investigated concepts to represent tasks that are shared between (collaborative) robots and human beings [29] and to describe their interaction [5]. In contrast, we already introduced the ADAPT (Action-Decision-Asset-Property-Relationship) modeling approach in [19], which is a customized and extended version of BPMN to support industrial settings and applications. It enables the rule-based and abstract modeling of assembly (production) workflows in a generic manner without thinking of hardware specific constraints. This abstract behaviour was shown in [18], where the approach was applied for skill-based automation systems using OPC UA and in [8], where it was used for modeling assembly tasks including suitable assistive systems.

3. Concept

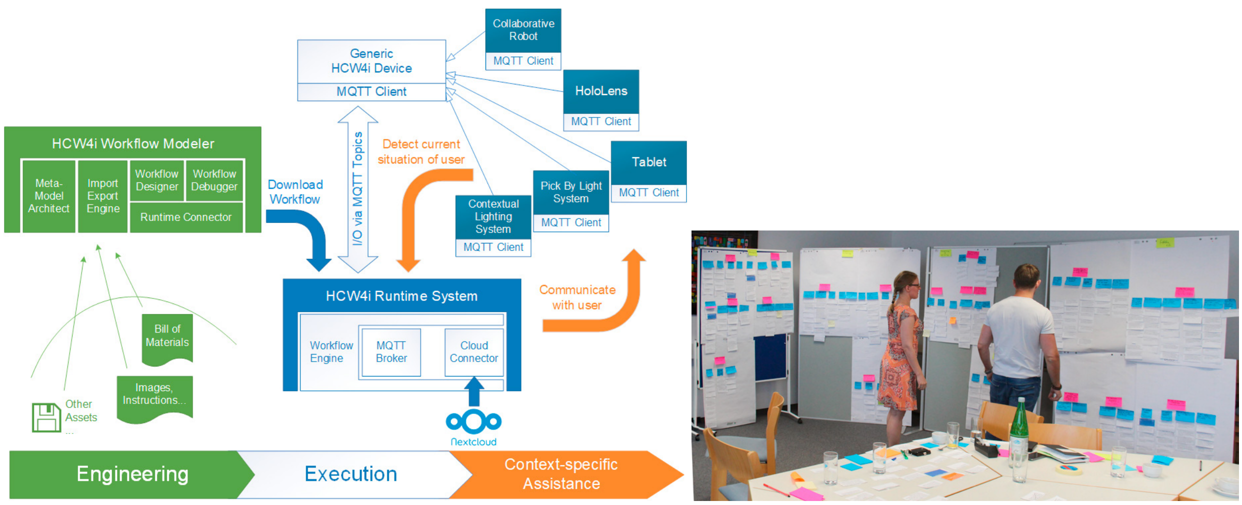
The overall concept of our research approach results from a 4-year research project called "Human Centered Workplace 4 Industry (HCW4i)" , which started in 2016. This project and its associated research aims at designing universal methods and systems for digital assistance of production employees at the workplace and ensuring a safe interaction between human and machines through sensor-based situation and status recognition. To this end, prototypic assembly workplaces, which are equipped with various industrially applicable assistive systems have been designed. The configuration of the workplace, its assistive systems and the work steps to be accomplished are defined using a new domain-specific language (DSL) approach called ADAPT [19]. This approach enables a holistic modeling of discrete assembly processes, human-machine interaction and the associated hardware devices supporting the following three aspects of operation as shown in fig. 1a: (1) The first aspect deals with the overall engineering providing a modeling method for assembly workflows and a prototypic software toolchain for assistive operation. (2) The second aspect supports direct execution of assembly workflows featuring a runtime system and reference workplace for assembly tasks. (3) The third aspect addresses context-specific assistance on a process level by defining a user-oriented contextual design process and corresponding evaluation and/or technology prototypes for contextual awareness. To enable these aspects, a prototypic software ecosystem has been built featuring an integrated development environment including a workflow modeler and a workflow debugger. Furthermore, a runtime system directly executing workflows and interconnecting each assistive system using MQTT (Message Queuing Telemetry Transport) has been implemented. For accomplishing detailed evaluations, a reference implementation of an assembly workplace featuring several assistive systems has been implemented. The workplace is fully operated by the developed software and described in more detail in section 5. Beside the software/hardware aspects our approach features a corresponding contextual design approach guiding a potential user through the process of implementing assistive systems in industrial environments as described in section 4. This process defines how to optimally provide feedback on the assembly operations carried out on the basis of the information from the workflow-model and the current sensor data.

4. Contextual Design

For our CD process we rely on data gathered in four CIs and four additional interviews. The CIs and interviews were held at two companies, of which one company is a manufacturer of automation technology, and the other a manufacturer of welding machines. We focus on human beings carrying out manual assembly tasks and other stakeholders in contact with them. The CIs involved four production employees, and the standalone interviews included people in the roles of production line scheduler, shift supervisor, team leader and manager. We carefully selected our participants with direct involvement as key users in production environments. All acquired data was consolidated to build an affinity diagram and personas. This brought us in-depth knowledge regarding requirements for assistive systems in the area of manual assembly. The newly gained knowledge from this analysis was applied in our prototypes (see section 5 and [21]).

Contextual Inquiries **—** In CIs, the users take the role of a subject matter expert by talking about and demonstrating their everyday tasks. The interviewer acts as a curious apprentice and identifies the most relevant processes, procedures, potentials and problems. Our CI sessions included 1) an interview (60 minutes), 2) an observation at the users' workplace carrying out everyday tasks (45 minutes), and 3) a final wrap-up to clarify open questions (15 minutes). All observations consist of the assembly of a complete product in a production line with several stations. One observation took place in the context of training where the participant got step-by-step instructions from an experienced colleague. All interviews were recorded with audio and the observations with video for later analysis. In our inquiries we gathered about 13 hours of audio recording, 10 hours of video, about 150 photographs and 35 pages of written notes.

Contextual Analysis **—** With the help of CIs we captured the "voice of the assembly worker" and transformed the data in the CA phase into affinity notes. Affinity notes describe events, problems and issues in the context of our users and are the basic building blocks of the CD methodology. The affinity notes are then organized in an affinity diagram (see fig. 1b) which is hierarchically structured grouping the note into key issues. The next steps included the deduction of requirements and the derivation of valid design ideas. For this, we hold a so-called *Wall Walk Workshop* where we introduced stakeholders (with different professions and experiences) from outside the core inquiry and analysis team to the data. In this workshop, the participants inspected the affinity diagram and placed sticky notes of emerging ideas or issues directly on the diagram. Through a wide variety of individual and personal experiences of the participants, a wealth of design ideas for solving problems in the data could be generated. These design ideas were then discussed and evaluated together with all participants. The results were incorporated into all further developments, steps and prototypes.



(a) The overall concept: engineering, execution and context-specific assistance.

(b) Researchers building the affinity diagram.

Fig. 1. The concept based on the contextual design process.

5. Software ecosystem

This section covers the explanation of different approaches carried out in the course of this project. Each approach includes identified challenges, an explanation of the created prototype and the lessons learned throughout the project.

5.1. Interdevice-communication

One of the aims of our work was to create a prototype of an assistive workbench (see fig. 2a) to support manual assembly. This subsection covers every communication between different devices of said prototype and explains the devices themselves.

Challenges — Due to the fact that this system consists of many different interacting components and scientific fields, three crucial challenges were examined, the first being *usability*. Because of the number of in- and output devices, usability is a very broad challenge. This usability interaction must be well thought through for a wide range of use cases. In addition, it is crucial to enable optimal usability for a broad range of user demographics, covering user characteristics such as familiarity with technology or body height. *Performance* is in direct relation to usability and the user. Good performance means fast and latency-free communication between devices with little waiting time for the user. To achieve this, the devices must efficiently handle the computing effort and the communication interfaces must be able to cope with the amount of data sent. The communication protocols used must be fast, easy-to-use and applicable on a large number of different systems. The interplay of the said different systems highlights the challenge of high *stability*. A lack of this property can again disrupt the user in the successful task execution, as well as *inconsistency*. The user should never be responsible for solving an occurring software or hardware problem, but rather be unaware of any of them since they are being resolved in the software without disturbing the user.

Prototype — The basis of the assembly workplace has been enhanced by adding numerous input and output devices and the so-called device manager. The device manager, running on a Raspberry Pi 3B+, sends and receives data via MQTT, which is a protocol based on a subscription-publishing model. MQTT works well for prototyping, since it is lightweight, easy to implement and available for many different systems. MQTT is not suitable for visual data like images or videos, for which HTTP is being used. The device manager receives commands from the Runtime (see fig. 1a) and executes them on the wire-connected actuators. The actuators work as assistive tools (e.g. pick-by-light), whereas the sensors measure predefined actions which are executed by the user. Additionally, it monitors the built in sensors and notifies the Runtime about changes via MQTT. Furthermore, the device manager is connected to Bluetooth user-input devices such as buttons and a foot pedal. Unity3D is used for visual feedback. The monitor (beneath the see-through table surface), projector, tablet and Microsoft Hololens display assembly information on their screens or in-situ. Auditory feedback is given through the tablet, which includes the machine as well as text-to-speech translation of textual work instructions. To support further user demographics it is possible to adjust the height of the workplace for ergonomic purposes. A smart toolbox signals to the user via LEDs which tool to use for the current assembly step, which can for example be handed to the user by a robot.

Lessons learned — Concerning *usability*, machine-translated work instructions has been deemed problematic after the evaluation described in [12]. The currently used machine-translation is of insufficient quality to clearly identify which assembly parts to take or where to put them. To make matters worse, the translations were *inconsistent*. In contrast, the implemented text-to-speech functionality is more promising. The first iteration of the workplace prototype used multiple Arduino Megas for sensors and actuators, all controlled by a MAC mini running a Unity3D application as the device manager. We examined several communication problems between the Unity3D application and the connected Arduinos via the serial interface. Communication was enabled by the Uduino library available on the Unity Asset Store. To improve *performance* and *stability* and fix this problem, we reduced the number of devices in use. Thus, the MAC Mini, all Arduinos and connected hardware were replaced by a Raspberry Pi 3B+ Single-Board-Computer (SBC) acting as the new device manager. Connection issues to the Hue-Bridge controlling the Philips Hue Lights could also be resolved through this measure. The use of the Raspberry Pi involved certain hurdles. Initially the SBC was connected to a PiXtend v1.3 expansion board via SPI, which extends the connection and application possibilities of the Raspberry Pi. Because of the large communication overhead between the two no reliable data could be read out of the ultrasonic sensors, so the PiXtend was removed. With regards to Industry 4.0, OPC UA and not MQTT is a promising data connectivity standard [24]. At first glance, MQTT and OPC UA work similarly, but the latter additionally offers end-to-end encryption and access to machine meta data (for data analytic tasks). As a result, we will either replace MQTT by OPC UA or support both protocols in the future.

5.2. Workflow modeling and execution

Prior to the integration of assistive systems, the assembly workflows should be specified or modeled in detail. As a result, it is possible to evaluate and integrate suitable systems into the production workflow to support human workers depending on their needs and experience levels. The modeling process of production workflows should be flexible enough to allow fast and intuitive updates. Thus, it is possible to update and implement the workflows depending on the domain specific requirements and fast changing market demands. Nevertheless, the modeled workflows must be defined to such an extent, that it is possible to execute them immediately with a corresponding and proprietary execution system.

Challenges — The modeling and subsequent execution process imply several challenges for the end-user and the entire software ecosystem:

(1) Usability: Defining workflows can be difficult for users that are not familiar with the well-known modeling languages already mentioned in section 2. The overall modeling and execution process of manufacturing tasks must be as intuitive and flexible as possible.

(2) Validity: The validation of assembly workflows is crucial to support their instant execution. Therefore, it is possible to specify rules for a domain specific type of assembly workflows with the help of a meta model. For example, a possible rule could be, that a "grip" action must always be followed by a "release" action. As a result, the user is informed when an important action is missing or an invalid sequence of work steps is modelled. Thus, it is possible to correct semantic modeling errors in the workflows offline before they are executed.

Prototype — For the orchestration of required assistance systems (e.g. visualization, pick-by-light, robot, etc.), a complete software solution has been implemented. The Workflow Modeler application (see fig. 2b) offers the possibility to model workflows including all relevant assistive systems. As a result, the user can focus initially on the workflow itself which describes the production process of a product type. Subsequently, various suitable assistance systems can be integrated into the production workflow. Thus, it is possible to simultaneously model the way of producing a product and to orchestrate assistive systems that support human workers during their daily work routine within one tool.

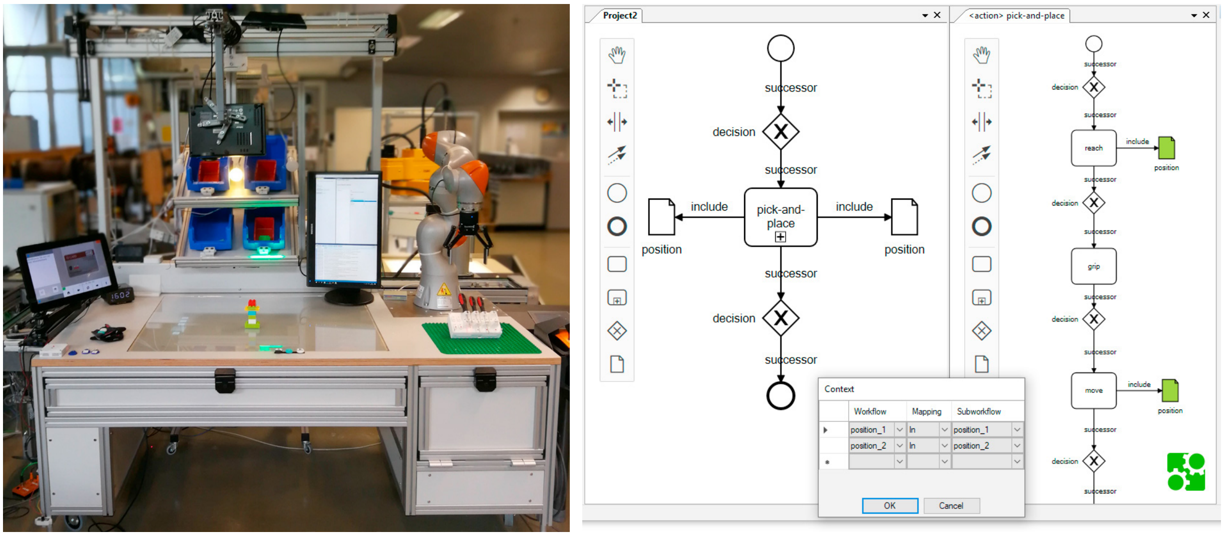
Lessons learned — The most important factors for the effective and value-adding usage of the presented modeling and execution system are the performance, usability, flexibility and expandability of the software. For this purpose, we organized several evaluations and software usability tests with test personnel. As a result, several improvements in the software could be achieved which lead to an increasing user experience of the system. During the implementation and test phases of the overall modeling system and the subsequent execution system, several problems occurred which implied additional features for the modeling software.

(1) Complexity: The complexity of the modeled workflows increased depending on the granularity of worksteps and the application domain. This led to unclear and enormous graphical models of the workflows. As a result a *subworkflow* feature has been implemented. This allows the user to define enclosed subworkflows, which structure assembly workflows hierarchically. As shown in fig. 2b for example a "Pick&Place" subworkflow is defined, which can be reused and parameterized in other workflow models.

(2) Expandability: Besides the modeling of assembly workflows, companies often desire features that imply additional benefits during or after the orchestration and modeling of production processes. This could be for example an auto-generation feature of visualizations that show work instructions to human workers, offline-debugging of workflows or proprietary data importers to automatically create new assembly workflows. For this, the Workflow Modeler application supports a plugin interface that allows users to expand the application with customized plugins.

5.3. Picking support and object tracking

Another important building block that has to be covered by an assistive system for manual assembly is to determine whether assembly workers use the correct parts and tools for their work steps. As production environments typically use container bins for storing parts and auxiliary mounting material, we want to ensure that the parts are picked from



(a) The assistive workbench prototype.

(b) Modeling process using the Workflow Modeler.

Fig. 2. The assistive workbench setup and the modeling software.

the correct bin and that no wrong parts are assembled in the final product. Therefore, we evaluated technologies for tracking hand movements via vision-based and ultrasound-based approaches.

Challenges — Industrial solutions for manual picking, such as Pick-by-Light, may be expensive and complex. When it comes to prototyping and evaluating assistive systems for manual assembly tasks, we see the need for lightweight and low-cost systems that can be easily adapted to changing environments. Traditional off-the-shelf Pick-by-Light systems are typically delivered as highly integrated hard- and software ecosystems which involve complex configuration and therefore often do not meet these requirements. On the other hand, low-cost systems must be usable in industrial environments and provide appropriate robustness and accuracy (e.g. for evaluations). Choosing an appropriate technology or system is an important aspect. Depending on the use case, requirements such as size, weight, installation and maintenance effort, tracking resolution may be selected. For example, vision-based systems require a clear line-of-sight. However, this is not always possible in real world industrial settings: objects of interest may be occluded or out of sight. In such cases, alternative or integrated approaches are necessary.

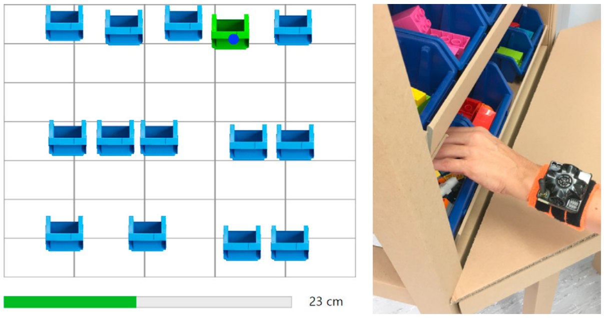
Prototype — For our part-picking assembly support system, we implemented two prototypes:

(1) Kinect Prototpye. The prototype uses depth data from the Microsoft Kinect to detect the picking of assembly parts. A configuration tool (see fig. 3a) is used to define and edit areas for bins. All these virtual bins are described with their position, height and width in a world coordinate system as well as a depth value. In order to detect the picking of parts, the system checks if the worker's hand is present in a virtual bin by comparing the actual depth data with the configuration data. If the result exceeds a certain threshold, a picking action has been successfully detected.

(2) Prototype Marvelmind. The prototype is initialized with a layout configuration containing coordinates of all bins of a workstation. It includes a calibration mechanism for an easy configuration of the positions of the bins. The system receives the 3D coordinates of the mobile beacon worn on the hand of the user. The system can then determine if parts are removed from the correct bins and display the next instruction. The prototype includes a separate visualization showing the real time position data of the transmitter and its coordinates within the layout configuration (see fig. 3b).

Lessons learned — Mounting and installing sensor systems in real world settings is often difficult. Workplaces on the shop floor are highly optimized and there is usually no space for additional sensors or hardware, unless the workplace is completely redesigned. Requirements like a mandatory line-of-sight cannot be easily satisfied. This should be taken into account when setting up test and evaluation environments. Low-cost systems can provide sufficient accuracy. For example, our evaluation of the Marvelmind prototype showed that a localization accuracy of $\pm 2cm$ can be achieved. The integration (e.g. in a manufacturing execution system) and maintenance have to be done by the user and can involve considerable effort.

(a) Tool for configuring areas for the detection of picking events based on depth data from a Microsoft Kinect.



(b) Screenshot of the visualization component with the bin layout and real time information of the current position of the beacon (blue circle). Marvelmind beacon is placed directly on the worker's wrist.

Fig. 3. Picking support and object tracking.

5.4. Vision-based recognition of assembly steps

We see the vision-based recognition of assembly steps as an integral part of this project for matching the work performed by a user to a modeled workflow with multiple steps. Vision-based approaches can be used to extract positional information of objects (e.g. parts and tools) from images. In the course of this project, we applied and evaluated different approaches: 1) shape-based 2D matching using the machine-vision library Halcon and 2) object detection using Machine Learning (ML) techniques (e.g. Convolutional Neural Networks and TensorFlow).

Challenges — The parts and objects to be recognized can differ greatly in shape and size. In addition, components may differ only in their color (e.g. Lego bricks). Following the No Free Lunch theorem [31], there is no single strategy that is best suited for recognizing assembly parts and steps. Therefore, finding and choosing the best approaches differs for a given problem and use case. In special cases, it can be necessary to combine multiple approaches. Vision-based approaches generally require a stable environment. For example, this is necessary because the lighting conditions may affect the color values, which in turn may differ from the values in the reference model. Reflections on objects may also cause severe problems. ML-based approaches can offer some flexibility and deliver more robust results.

Prototype — In this project, we implemented multiple prototypes ranging from recognizing simple objects (see fig. 4a) to recognizing whole assembly tasks with multiple related work steps using deep learning. The use of convolutional neural networks (CNNs) was examined in more detail in order to measure the progress of assembly steps. The underlying data model uses training data consisting of images of the individual work steps instead of images consisting of individual components. Another approach was developed using the Tensorflow Object Detection API. In contrast to the previous approach, the work steps to be recognized not only rely on individual objects to be present in a scene, but also consider their spatial relationship with each other (i.e. part A is to the left of part B).

Lessons learned — Maintaining training data and models is expensive. Generally, it is laborious to collect and clean training data. For example, we captured around 250 images per object to be recognized. Labelling all images by hand takes multiple hours. Furthermore, new objects, changed parts or changed environmental conditions (e.g. different lighting conditions) must also be taken into account and reflected in the training data.

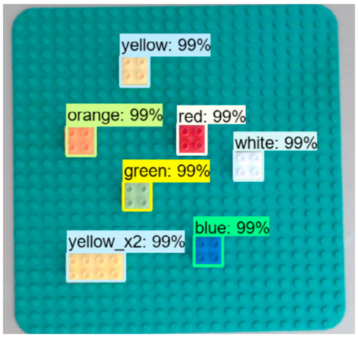
5.5. Digital work instructions

For assembly workers, the quality and presentation of instructions are essential. In real world industrial settings a variety of forms, types and modalities can be discovered, ranging from paper-based to interactive digital work instructions. Based on the findings in our human-centered design process, we iteratively built and evaluated multiple prototypes. Additionally, we explored the concept of AR instruction for supporting workers in carrying out their tasks by overlaying virtual information on real world objects.

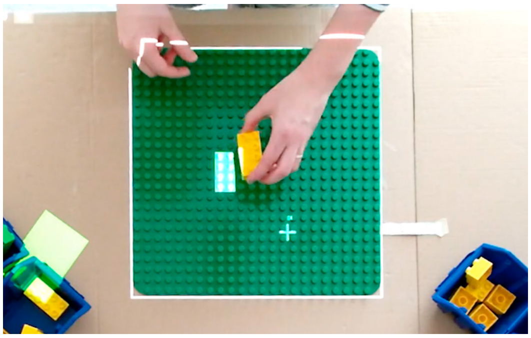
***Challenges* —** Results from our CA process revealed, that the authoring and maintenance of work instructions is often of low priority. We observed a lack of consistency and even missing work steps, which makes them even harder to read and understand. These are all issues that have to be solved before digital instructions can be introduced in a work environment. Designing effective work instructions is a challenging task. While fine granular work instructions are indispensable for freshman workers to learn and memorize new work steps, they may put drag on experienced personnel and yield higher task completion times. Therefore, designing work instructions for the appropriate experience level is important.

***Prototype* —** Following our human-centered design process, we created paper-based prototypes that were later transferred into a fully-interactive high-fidelity prototype on a tablet device. First interactive prototypes were created using the prototyping tool Axure RP and evaluated in a multiple-case study. The final version of the software prototype (see fig. 4c) was implemented in C# and Unity3D, enabling the possibility of displaying 3D models in the future. The prototype for AR instructions (see fig. 4b) allows the projection of different shapes and objects (e.g. circles, arrows, pictures, text). A calibration mechanism enables the interplay of different coordinate systems (world and projection coordinates) and is designed with an emphasis on extensibility (e.g. integration of additional shapes and objects). This ensures that projection-based AR instruction can be used in a flexible manner and in a wide range of assembly scenarios.

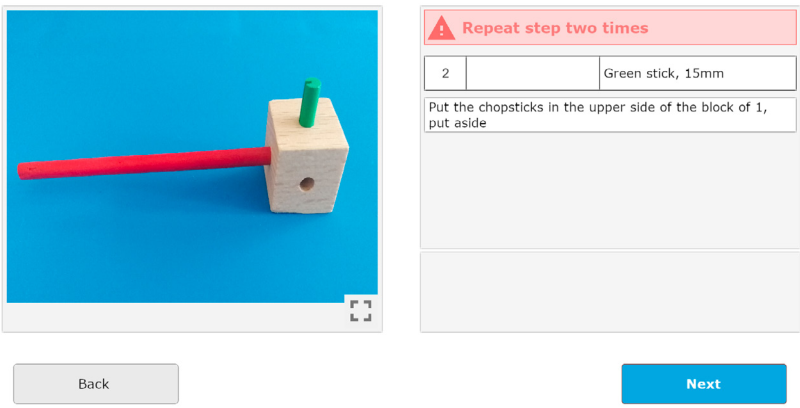
***Lessons learned* —** As digital instructions may provide interactive capabilities (e.g. zoom into photos), they can often be better understood than paper-based instructions. Feedback from users revealed that even static imagery might not suffice for complex tasks and that additional videos or animations would facilitate comprehension.



(a) Single frame of the TensorFlow prototype showing the detected Lego Duplo bricks.



(b) Projection-based AR instructions guiding the worker to the correct bin and assembly location.



(c) Prototype showing digital assembly instructions.

Fig. 4. Vision-based recognition of assembly steps and digital work instructions

6. Discussion

The overall goal to implement acceptable assistive systems is to find a balance between assistive measures and self-guided work. Unfortunately, this simple sounding goal (i.e. the balance) strongly depends on at least but not limited to the following factors: (1) complexity of assembly tasks, (2) experience of human workers, (3) setup of tools, (4) environmental conditions and many more. In modern assembly facilities, which produce a lot of variants, these factors change from one product to another. Therefore one of the most important points is enabling real context or situational awareness. This means the assistive system shall mostly autonomously detect the context of the current assembly situation (e.g. who is assembling, which product, which tools, etc.). This requires at least two important issues which shall be further researched: (1) Contextual Modeling - methods to define assembly workflows, relationships between assembly steps, tools, parts, etc. in order to enable a software base line for reasoning and detecting the current situation. Thus, assistive assembly processes have to be designed in an assistive way from the ground up. (2) Contextual Feedback - methods and tools to safely and robustly detect human actions and interact with human workers.

During the project several prototypes have been developed researching these two issues within the context of small-scale assembly processes (e.g. for personal computer assembly). The first is the prototype described in section 5.1. The assistive workplace has been enhanced through the update of the first POC. Nonetheless, there are still improvements to make, mostly regarding current situation detection and evaluating unmistakable but non-intrusive feedback. The workflow modeling process is crucial for the optimal configuration and orchestration of human-centered assembly workplaces. Only if the overall process itself is modeled and analyzed in detail, suitable user-centered assistive systems can be integrated. Important factors in applying the modeling and execution system are the performance, usability, flexibility and expandability of the entire software. These factors must be included in a continuous process of improvement based on several evaluations and usability tests. However, it should be noted that findings are rather difficult to transfer to real-world scenarios and applications. The high variability in modern production processes and environments requires a large amount of resources to adapt and configure such assistive systems to make them effective and accepted by the users. Additionally, these environments are often heavily optimized, which may result in further limitation (e.g. structural and spatial limitations for the installation of additional sensors and hardware). Generally speaking the outcomes may not be transferred to other domains directly, but our evaluations accomplished at industrial assembly lines beyond our prototypes led to promising results for other domains.

7. Conclusion and Future Work

The paper presented an industrial workplace that was developed according to human-centered standards. In the beginning there was a contextual design before the individual assistance measures were developed and evaluated. The workplace covers the integration of workflow modeling, for instance, so that assembly steps can be modeled beforehand and then executed directly at the workplace. The workplace also provides digital assembly instructions via a tablet, a screen or a head-mounted device like the Microsoft HoloLens. Several assistive systems like picking support with augmented reality and a vision-based system for the recognition of assembly steps provide those means so that the whole human-centered workplace can instantly track and guide the worker. In a next step, the entire workplace with all its assistive systems is to be evaluated in extensive user studies.

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