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AR-supported Human-Robot Collaboration: Facilitating Workspace Awareness and Parallelized Assembly Tasks

Rasmus S. Lunding
Aarhus University

Mathias N. Lystbæk
Aarhus University

Tiare Feuchtner
University of Konstanz & Aarhus University

Kaj Grønbæk
Aarhus University

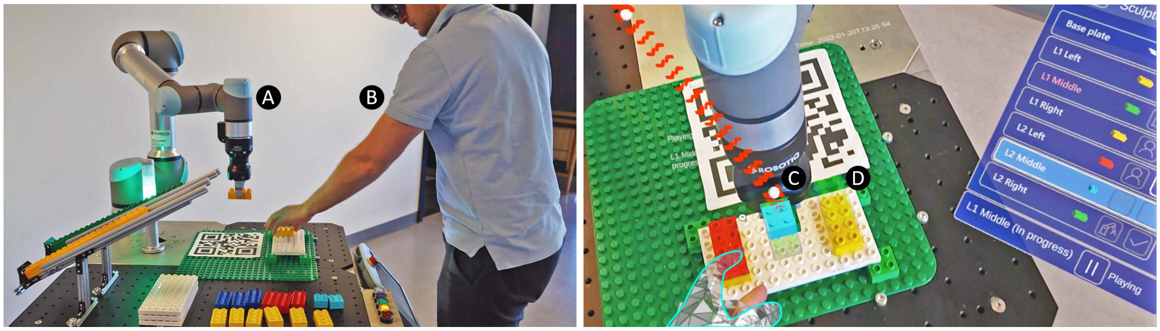

Figure 1: We present an AR-based assistant for collaboration in an assembly task between a (A) robot and (B) human operator in a joint workspace (left). We therefore present situated robot status information (e.g., movement path (C)) and task-related details (e.g., building instructions (D)) (right). Note: The path visualization and user's virtual hand are enhanced for better visibility in print.

ABSTRACT

While technologies for human-robot collaboration are rapidly advancing, plenty of aspects still need further investigation, such as ensuring workspace awareness, enabling the operator to reschedule tasks on the fly, and how users prefer to coordinate and collaborate with robots. To address these, we propose an Augmented Reality interface that supports human-robot collaboration in an assembly task by (1) enabling the inspection of planned and ongoing robot processes through dynamic *task lists* and a path visualization, (2) allowing the operator to also delegate tasks to the robot, and (3) presenting step-by-step assembly instructions. We evaluate our AR interface in comparison to a state-of-the-art tablet interface in a user study, where participants collaborated with a robot arm in a shared workspace to complete an assembly task. Our findings confirm the feasibility and potential of AR-assisted human-robot collaboration, while pointing to some central challenges that require further work.

Index Terms: Human-centered computing—Human computer interaction (HCI); Human-centered computing—Mixed / augmented reality; Human-centered computing—User studies; Computer systems organization—External interfaces for robotics

1 INTRODUCTION

Substantial development effort in the manufacturing industry is aimed towards automation to increase efficiency, reduce production expenses, and improve working conditions. However, the increasing demand for customized and tailored products often renders fully automated product lines impractical or unprofitable, due to high programming costs and lack of flexibility for adaptation. Thus a hybrid setup combining human operator(s) and robot(s) is interesting in such scenarios [36]. With the recent decade of development within collaborative robots (cobots), companies are offered an opportunity to increase productivity through partial automation, while retaining flexibility, as cobots can work alongside human operators and are generally easier to reconfigure for new tasks, compared to traditional industrial robots [38]. However, as of today, cobots still rarely collaborate with humans in a production environment [28, 38, 41].

Recent years have seen an increase in research for supporting collaboration between humans and robots [39]. Augmented reality (AR) has shown great promise to support this collaboration [51], in particular within: communicating robot intent (e.g., [2, 44, 52]), dynamic task allocation (e.g., [30, 45]), and step-by-step instructions (e.g., [3, 19]). These works show promising results within their individual subjects, however, there is a lack of work that explores how these topics influence each other.

To address this limitation, we present an AR system for supporting human-robot collaboration (HRC) by combining robot intent, dynamic task allocation, and step-by-step instructions. Our system supports: 1) Robot status display and action preview: The operator successively receives communications from the robot, about how it will perform the current operation (e.g., visualization of movement path) and what other actions it plans to do afterwards. 2) Task overview and allocation of operations: The operator can view the planned tasks in a kind of "*task list*" and manage the list of operations. We enable the operator to dynamically delegate suitable operations to the robot as the work is progressing. 3) Step-by-step instructions: The AR interface offers step-by-step guidance for assembly operations that are allocated to the operator, through situated visualization of relevant information.

In this work, we consider the industrial scenario of injection mold assembly, which involves a number of heavy components and repetitive tasks, where assistance from a robot is beneficial. To effectively support such collaboration, the operator is instrumented with a Head-Mounted Display (HMD), which enables persistent visualization of critical information within the operator's field of view, as well as situated visualization in the workspace. Furthermore, it allows the operator to freely manipulate tools and workpieces, as it supports hands-free interaction and can capture multi-modal input from the operator (e.g., gestures, voice commands, eye gaze).

We evaluated our system in a lab study with 18 participants. In our lab study, the participants were asked to do assembly tasks with a collaborative robot. For the sake of replicability, user safety, and to reduce confounds due to technical expertise, we designed a simplified task with DUPLO bricks, instead of the injection mold

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assembly. We argue that this simple task is sufficient to show the strengths and weaknesses of the proposed AR system, as our primary aim is to evaluate the interface components and interaction with the robot, not the actual assembly procedure.

With our work, we contribute 1) an AR system that combines: communication of robot intent, dynamic task allocation, and step-by-step instructions in order to support a human operator collaboratively performing an assembly task with a robot, 2) we present insights from a user study, highlighting the main opportunities and challenges of AR-based guidance, compared to a more traditional tablet-based interface, 3) new directions for human-robot collaboration. to inform the future design of collaborative human-robot interaction systems and point out directions for future research.

2 RELATED WORK

Human-robot collaboration can be classified as a sub-category of human-robot interaction, with multiple proposed definitions considering various dimensions [1, 26, 37, 45]. Attempting to consolidate these and resolve contradictions, Aaltonen et al. [1] propose four levels of collaboration: *no existence*, *coexistence*, *cooperation*, and *collaboration*. Collaboration is thereby the "highest" level of interaction, which takes place when the "human and robot work simultaneously on a shared object in shared space" [1].

In the following we will discuss related work from mainly three areas within HRC research: (1) facilitating communication and workspace awareness, (2) supporting task completion with AR, and (3) dynamic task allocation and execution.

2.1 Enabling communication and workspace awareness

Breazeal et al. [9] postulates that implicit non-verbal communication positively impacts human-robot task performance with respect to the understandability of the robot, efficiency of task performance, and robustness to errors that arise from miscommunication. One line of research has explored this in the context of designing familiar (i.e., human-like) and therefore predictable movement patterns [6, 20]. More commonly, communication of a robot's intent happens through the presentation of digital information [44], e.g., by visualization of the planned movement path in AR. Providing AR guidance is typically done in three ways: through a display situated in the operator's environment [5, 13, 33], through projection mapping on surfaces [2, 19, 24], or with an HMD displaying content directly in front of the operator's eyes [11, 35, 42, 46, 49]. How to best achieve this depends on the context, task and available user interface. For example, in a collision monitoring task, Rosen et al. [48] found a path visualization presented in an AR HMD preferable to a monitor or no visualization at all. On the other hand, Hietanen et al. [24] found projection mapping to perform better than an HMD (HoloLens 1) to indicate robot movement zones during an assembly task. Several papers present variations of designs for line-based path visualizations that proved effective [3, 17, 56]. In the context of flying drones, Walker et al. present a design space [55] proposing further variants for communicating robot motion intent in AR, like direction indicators (e.g., arrows) and navigation points.

Motion intent is not the only relevant information for improving the operator's situational awareness in collaboration with a robot. For example, Pascher et al. [44] propose aiding the understanding of planned robot motion by additionally communicating the need for attention, robot state, and user instructions to intervene. Several papers propose projection-based AR interfaces to display information about the robot's current status, including task instructions, warnings, and task completions [2, 21]. Further, Andronas et al. [3] support a wide range of information visualizations (status, instructions, movement intent, etc.) for workspace awareness across multi-modal interfaces - i.e., permitting the user to interact through various interfaces (AR HMD, smartwatch, phone, etc.). An excellent overview of design and strategies for supporting situational awareness can be found in the comprehensive review Suzuki et al. [51].

Building on prior research, our AR system includes a path visualization [17, 56] and further visual cues, such as holograms [3, 4, 25, 58], to enhance the operator's workspace awareness. In contrast to most of the work reviewed here, we contribute an evaluation of the proposed approach through a user study involving authentic HRC, i.e., participants interact with an industrial collaborative robot in a shared workspace. This allows us to explore pertinent issues related to perceived safety and sense of control, operator's collision avoidance strategies, and workspace awareness during collaboration.

2.2 Supporting task instructions with AR

A key requirement for presenting situated instructions in AR is the accurate registration of this content in the real world. This requires alignment of several coordinate systems, such as the robot-internal representation of the work area, the AR system's world coordinates, the model of the current workpiece, etc. Similarly to multiple other systems [7, 12, 14, 29, 58], we employ marker tracking with a QR code (see Sect. 3.3). To improve tracking accuracy and reliability to within 1mm, Yan [58] employs several markers in their proposed BRICKxAR - a novel instruction method for AR construction guidance with LEGO bricks.

A second consideration that must be made concerns the type of information and visualization that is used to convey instructions to the user. For example, the intended placement of physical components can be indicated by visualizing the respective holograms in their target position [3, 4, 25, 58]. Further, labels presented for virtual objects [58] (similar to how object detection algorithms indicate which object is recognized) can aid their identification. Animating components, as proposed in e.g. AdapTutAR [25], can additionally convey the dynamics of how components should be manipulated or in what way they need to be placed.

Inspired by these works, our system conveys information to the user, including the status and movement intent of the robot, and instructions for the operator's current task. Furthermore, we present a *task list* to indicate the overall progress in the assembly sequence, the remaining tasks and where work can be done in parallel.

2.3 Lack of support for dynamic task allocation in AR

While Mahadevan et al. [34] found that implicit task allocation led to faster completion times and more simultaneous activity of both actors, it was also found to lead to more robot errors and a reduced feeling of being in control for the operator.

Several attempts have been made to create scheduling algorithms for assembly tasks, each with various focus [16, 27, 31, 45, 53]. Parameters that can be considered are the capabilities of each agent, the time taken to perform an action, the agent's availability, success rate, ergonomics, and more. The most recent attempts to implement dynamic task allocation [45] found it to reduce the overall cycle time compared to both manual assembly and static task allocation, however, only used a tablet as a user interface. While Lamon et al. [30] used AR for their comprehensive architecture for dynamic role allocation and collaborative task planning in mixed human-robot teams, their interface and user study are focused on task allocation.

In our system, we support dynamic task allocation and parallel task execution, such that the operator and robot can work simultaneously. We focus on how to incorporate this in a broader system and what implications it might have.

3 AR-SUPPORTED HUMAN-ROBOT COLLABORATION

We consider assembly processes as predefined sequences of steps, each of which can be completed either by the operator, the robot, or both, either sequentially or simultaneously. Importantly, we envision the operator in a supervisor role, with the option to delegate steps to the robot. The central challenge in the system design is to define a shared assembly model, such that the operator and robot use the same data source. This should also support the parallel execution of (some) tasks and incorporate ideas from related work to communicate the status of the robot. These aspects are discussed in more detail in the following sections.

3.1 Shared assembly model

In industrial manufacturing, a Bill of Process (BoP) is typically a step-by-step list of tasks that describe how the operator assembles a product, where each step could potentially be done in parallel.

We have formalized the steps of a BoP by introducing three types: *products*, *tasks*, and *assembly sequences*. *Products* are physical components, used to create other products, e.g., a bolt, or something that has been assembled from other products, e.g., an injection mold. *Tasks* define an action involving one particular *product*, e.g., insert a bolt at a particular position in the mold. A task is a single step in an *assembly sequence*. Furthermore, a task might have pre-conditions, requiring previous tasks to be completed before it can be initiated. Lastly, an *assembly sequence* is a collection of *tasks*.

Since we assume that the operator and robot can perform a subset of the same tasks, a shared assembly sequence is used. Each task has pre-defined information, e.g., product, position, pre-conditions, and information about who can perform the task, used to show step-by-step instructions to the operator or invoke pre-programmed robot actions.

3.2 System overview and workstation setup

The system is currently distributed on three devices in our lab: a Universal Robot arm (UR5e [47], Polyscope: v5.9.1) mounted on a worktable, a mini-computer (ASUS PN51-E1), and an HMD (Microsoft HoloLens 2). While Hietanen et al. [24] found projection mapping to perform better than an HMD (HoloLens 1), we expect the recent advances in HMD technology (e.g., improved field of view of HoloLens 2) to make it a viable option.

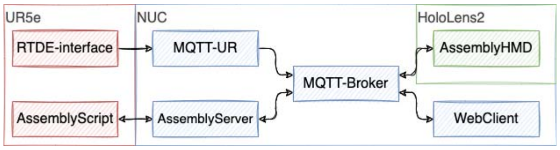


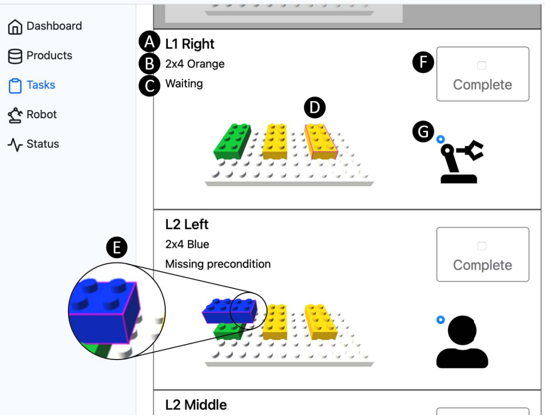
Figure 2: Illustration of dataflow between components in the system. MQTT-UR retrieves data from the robot's RTDE-interface via a socket connection. AssemblyScript retrieves data from the AssemblyServer via XML-RPC. The rest of the components communicate via MQTT.

It consists of seven software components, as illustrated in Fig. 2. If possible, components communicate via MQTT [43], which is a lightweight publish-subscribe protocol. A MQTT-Broker (Mosquitto v2.0.15, MQTT v3.1.1, [15]) is responsible for handling communication between the various components running on different devices. To retrieve real-time data from the robot, we employ the robot's built-in Real-Time Data Exchange (RTDE) interface (v2.7.1) [54].

The AssemblyServer running on the mini-computer handles the assembly process, which entails loading *products*, *tasks*, and *assembly sequences* and maintaining the status of any ongoing assembly sequence. The AssemblyServer is the backend for the *task list* which both the AssemblyHMD and WebClient communicate with through the MQTT-Broker, allowing for starting a specific assembly sequence, updating the status of a task, re-assigning a task, and showing the robot's movement path for a specific task.

The AssemblyScript, a UR-script running on the robot, polls the AssemblyServer for tasks to be performed. The AssemblyScript notifies the AssemblyServer about the current status of the task being performed. Furthermore, the AssemblyScript has additional safety features on top of what is built into the robot [26], which monitor applied forces during all robot actions, and immediately returns to a neutral position if excessive forces are applied. Joint moves are used for longer transitions (e.g., when moving towards the place point) with parameters set to $movej(a = 0.7rad/s^2, v = 0.5rad/s, r = 0)$, which corresponds to a joint acceleration of $40deg/s^2$ and speed of $30deg/s$. For more fine-grained movements, the robot used linear moves (e.g., when placing a brick) with the following parameters for maximum tool acceleration and speed and no blend: $movel(a = 0.5m/s^2, v = 0.15m/s, r = 0)$.

The AssemblyHMD and WebClient, handle sending commands from the operator to the robot and visualization of the assembly sequence on the HMD and tablet respectively. This includes the *task list* showing the name of the task, an illustration of the product, the current status (not completable, completable, and completed), a complete button, and an indicator of who will perform the task. The WebClient also visualizes where the product is to be placed, by showing an image of the current assembly progress with the current product highlighted (see Fig. 3). For the AR HMD this is designed as a situated visualization, as described in the following section.



L1 Right
2x4 Orange
Waiting

L2 Left
2x4 Blue
Missing precondition

L2 Middle

Figure 3: Screenshot of the AssemblyWebClient on a tablet. Each task item contains (A) the name of the task, (B) the product name, (C) the current status, (D) an illustration of where the product must be placed, (E) highlighted by a purple outline, (F) a complete button, and (G) an icon indicating whether the operator or robot is assigned to the task. This screenshot has been adapted for print, as a dark color-theme was used for the study.

3.3 HMD interface

The interface of the AssemblyHMD, implemented in Unity (2020.3.13f1) using the Mixed Reality ToolKit (MRTK v2.7.2), includes a *task list*, instructions, the robot's movement intent, and controls for the robot. The principal features are described in more detail below. To maintain a shared coordinate system between the AR application and robot work space, a QR code is attached in the work area with a known offset to the robot that forms a fixed point in the real world. This marker is continuously scanned using the built-in QR code tracking functionality of the HoloLens.

The AR *task list* is presented as a mid-air menu listing each task to complete (see Fig. 4). When the operator selects a product to be made, the assembly sequence definition is fetched and the list is populated. However, not all tasks are immediately be workabl, as some tasks have preconditions that need to be fulfilled. In our scenario, only the first task is available initially and the next tasks become active only once the first is completed. When designing our *task list* interface, we took inspiration from a music playlist for the layout and functionality: like enqueuing, playing, and pausing songs, the operator can assign tasks to the robot and command it to "play" or "pause" its task. For each task we predefine which of the agents is capable of performing it (either operator, or robot, or both). Consequently, if the robot arrives at a task in the queue for which the precondition(s) is not met, e.g., because the operator first needs to finish another task, it must wait for this, and vice versa.

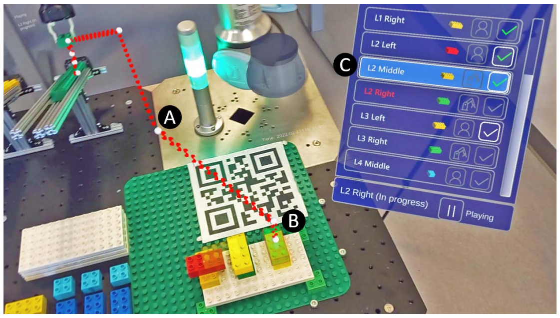


Figure 4: Visualization of the robot's path (A) for solving a specific task (C). In this case, picking up a green brick and placing it at the appropriate position (B). Note: For better visibility in print, we enhanced the path visualization.

Simple situated step-by-step instructions are conveyed to the operator: When a task is available (i.e., preconditions are met), a hologram of the product is shown at its intended position in the finished product, as can be seen in Fig. 5. Similarly, if the operator selects a row in the AR menu to inspect it, a hologram of the product required for that task in the construction space as a preview. Additionally, holograms for all products of any incomplete tasks that form preconditions are also visualized. To distinguish between the robot's and operator's tasks, a blue outline is added to all tasks assigned to the robot.

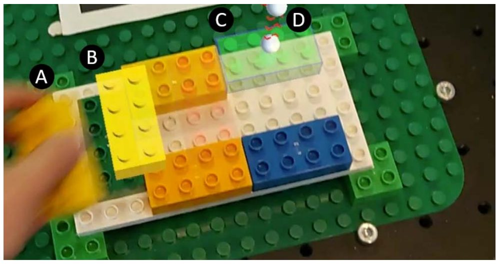


Figure 5: Two holograms are visualized in the workspace: The orange brick on the left (B), that the operator is placing (A), and the green brick on the right (C) that is worked on by the robot (D).

We show a situated visualization of the robot's planned movement path, with red arrows pointing in the direction of travel between waypoints programmed into the robot's movement. The path is shown to the operator under two circumstances: Either if the robot is performing a task, or if the operator is inspecting (i.e., has selected) a task assigned to the robot.

4 EVALUATION

We evaluated the system described above in a user study with 18 participants. This section first describes our study design based on our research goals, followed by the study task and overall procedure.

4.1 Study design

We compared three conditions in a within-group study design, counterbalanced using Latin Square [8] with Williams design [57] to compensate for first-order carryover effects. We varied the independent variables **interface type** and **task allocation**:

cTab: *Tablet Interface*. The *task list* is shown on a *tablet* (WebClient, running on a 12.9-inch iPad Pro) placed near the construction space, manipulated through touch input. Building instructions are presented as pictures comparable to paper-based LEGO building instructions. The task allocation is *predefined*. The interface can be seen in Fig. 3.

cAR: *AR Interface*. The *task list* is shown through the *HMD* (AssemblyHMD running on a HoloLens 2) manipulated through mid-air interaction. Building instructions are presented as holograms that are superimposed on the construction space. Further, a path visualization informs the operator about the robot's next movement. The task allocation is *predefined*.

cAR+t: *AR Interface w. Task Allocation*. The setup is identical to *AR Interface* (**cAR**); however, task allocation is partially *free* so the participant may reassign them if he/she would like to.

Our study aims to explore the following questions: (RQ1) How does our proposed AR solution impact HRC in comparison to a state-of-the-art (non-AR) interface? (RQ2) How can we effectively convey robot intent and task instructions through situated AR visualizations? (RQ3) How can we facilitate interactive task scheduling during HRC and effectively represent multiple parallel sequential procedures?

We aim to answer these questions through two pairwise analyses of our study conditions. Firstly, we compare **cTab** with **cAR** to evaluate our proposed AR interface in comparison to the state of the air, i.e., touch panel. Thereby allowing us to explore the *usability* of the mid-air menu and the *usefulness* of situated building instructions and real-time robot information. We expect to encounter typical issues of mid-air interaction (e.g., fatigue, lack of haptics, and erroneous selection) compared to tablet interaction. However, we expect that the AR interface will effectively support the task and that the situated visualizations provide improvements to the operator's *awareness* and *understanding* of the collaboration with the robot.

Secondly, we compare **cAR** with **cAR+t** to explore how the ability to coordinate tasks through the *task list* affects participants' *sense of control*, *confidence*, and *perceived effectiveness*. We expect that participants gain a stronger sense of control of the building procedure when forced to engage more with the *task list* and explore the system's scheduling functionalities more in **cAR+t**. A comparison of **cTab** and **cAR+t** is omitted as two factors are varied between the conditions (both interface type and task allocation) and any resulting effects could not be clearly attributed to either.

4.2 Study task

We designed an abstract DUPLO building task with the aim of allowing study participants to engage with our proposed interface using both the **cTab** and **cAR**, without the limitations, challenges, and confounds involved in replicating a complicated mold assembly setup. The use of DUPLO aims to simulate an arbitrary assembly task, where the study participants collaborate with a robot in joining multiple components to form a finished product.

With the use of DUPLO, the components do not vary in shape or size and can be easily combined. These simplifications were made to minimize the possible confounding factors between participants of technical skills and dexterity required for real-world tools. We argue that our simplified scenario is representative of HRC in assembly tasks, allowing conclusions to be made on the efficacy of our proposed *task list* and information visualizations in AR.

During the *Trial* runs, the participants were asked to collaborate with the robot to assemble one of the three construction designs shown in Fig. 6. These distinct designs, each consisting of 9 to 10 bricks on a base plate. Every participant created each of the construction designs in the depicted order, while the order of the conditions was counterbalanced. construction designs used during the *Tutorial* phase were similar to those of the *Trial* phase, although with different colors to limit memorization.

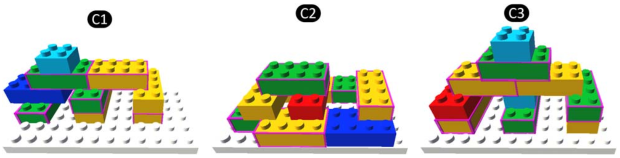


Figure 6: The constructions built by participants in trials 1-3: Construction 1 (left) and Construction 2 (middle) are each composed of 10 bricks, while Construction 3 (right) has 11 bricks. Bricks with a magenta outline were pre-assigned to the robot.

Importantly, green bricks were only for the robot, while yellow bricks were for both the robot and the participant to use. The remaining colors, and the white base plate, were only for the participant. The constructions were carefully designed to be of similar difficulty, with a similar number of shared yellow bricks.

4.3 Participants

Overall, 18 participants were invited to complete the study. Participation was voluntary and, as is usual at our institution, no financial remuneration was offered. The study participants (age: avg. 29.56 years, SD 6.76 years; gender: 4 female, 14 male) were predominantly students (10/18) or researchers (5/18) at the Department of Computer Science of our university. Most participants (15/18) had a background in Computer Science , and half (9/18) had prior experience with head-mounted AR technology.

4.4 Procedure

Participants arrived individually and were informed about the scope of the study. They were then asked to complete a consent form, confirming (1) understanding of potential risks, (2) voluntary participation, (3) collection and use of anonymized data, and (4) that consent can be revoked, and they can quit at any time. Participants then filled out a demographics questionnaire and were introduced to the study environment and tasks, including information on the robot's safety measures and the study procedure, see Appendix A.1.

The study was split into three consecutive phases: *Tutorial*, *Training*, and *Trial*. The *Tutorial* and *Training* phases were added to ensure that each participant had sufficient knowledge to perform the task. In the *Tutorial* phase, participants were taught how the two interface types worked: (1) to inspect and allocate tasks using the *task list*, (2) to locate building instructions, and (3) to interpret task and robot-related information. For the less familiar AR interface, some additional steps were required: after donning the HMD, participants completed a quick eye calibration and a direct manipulation task in which they practiced pressing buttons on a mid-air keyboard , as pilot studies had revealed difficulties with such interactions. The participants were then informed about how the colored bricks were allocated, as described in Sect. 4.2. Finally, the experimenter demonstrated the robot's safety measures, including having the participant start a task, where the experimenter blocked the robot's path with their hands. The demonstration served to make the participants feel more at ease near the robot.

After the *Tutorial* phase, participants completed one *Training* session per condition (in counterbalanced order) during which the experimenter offered assistance, e.g., reminding participants to mark a task as complete. Furthermore, participants were encouraged to think aloud, and we observed their interactions with the respective interface to detect potential misunderstandings and issues.

After concluding the *Training* sessions, participants completed the *Trial* phase in each of the conditions without any aid (repeating the same order). After each study trial, two questionnaires were administered. First a NASA TLX [23] with an added question on Eye Fatigue, see Appendix A.2. Then followed our post-trial questionnaire, in which participants were asked in detail about their perceived performance, sense of control, and situational awareness during collaboration with the robot, as well as their understanding of the respective interface, the visualized instructions, and robot status, see Appendix A.3.

The study concluded with a semi-structured interview, in which participants were asked to reflect on their experience of using the different interface types, to gain further insights about the participants' overall conception and *understanding* of the interface metaphor and system functionality. Finally, participants received a short debrief and were permitted to ask questions, before departing. The average duration of the study was around 1 hour and 15 minutes.

5 MAIN FINDINGS

To analyze the collaboration between the human and the robot, we explored whether both agents worked simultaneously or took turns, what tasks participants preferred to delegate, whether the *task list* metaphor aided their understanding, and how they perceived the **cAR** generally. This was investigated through questionnaires, video recordings, interaction logs, and interviews. To analyze interview transcripts and observations from the video recordings (obtained from three angles: camera 1, camera 2, and HoloLens) we clustered similar findings into groups (affinity diagram). For statistical analysis, we used the Wilcoxon signed-rank test (paired groups) or Friedman tests with post-hoc Wilcoxon signed-rank tests with Bonferroni correction (more than two groups) in SPSS. Plots were generated using the Matplotlib package of Python [40].

To summarize the main findings: (1) the participants and robot worked in parallel, (2) two strategies were generally used to divide the work, and (3) the participants were generally aware of the robot's next action. The following sections offer further details.

5.1 Collaboration dynamics during assembly

An important part of the system design was to facilitate parallel execution of assembly sequences, i.e. by ensuring that the participant had the needed information to confidently work together with the robot. Thus, two important questions arise: How did the participants and robot work together, and how well was this supported by the presented information?

Our questionnaire results reveal that participants generally felt in charge of the building task, which was similar across all conditions (Q1), as can be seen in Fig. 7. They even felt similarly in control of the robot during the collaboration (Q13) across all conditions. Interestingly, in the interview, some participants commented that there was no real need to be in control of the robot, as it was completing its tasks independently. Further, when asked about collaborating with the robot (Q18), participants felt significantly more like they were working together in **cAR** compared to **cTab** (**cTab** vs. **cAR**: $p < .025$, **cAR** vs. **cAR+t**: $p = 0.03$; correction for multiple comparisons: $\alpha = 0.025$).

5.1.1 Work happens in parallel

Interaction logs reveal *when* tasks were initiated by the robot, reassigned by the operator, or completed by either agent. Unfortunately, determining the initiation of a task by the operator, and therefore also individual task completion times, is challenging, as participants could work on multiple tasks simultaneously, might be interrupted, or could briefly abandon their task to coordinate with the robot. Nevertheless, illustrating individual interaction sequences offers some insight into the dynamics of cooperation. For example, the exemplary timelines (p9, p13) illustrated in Fig. 8 show that the robot was continuously busy throughout the entire assembly process (blue

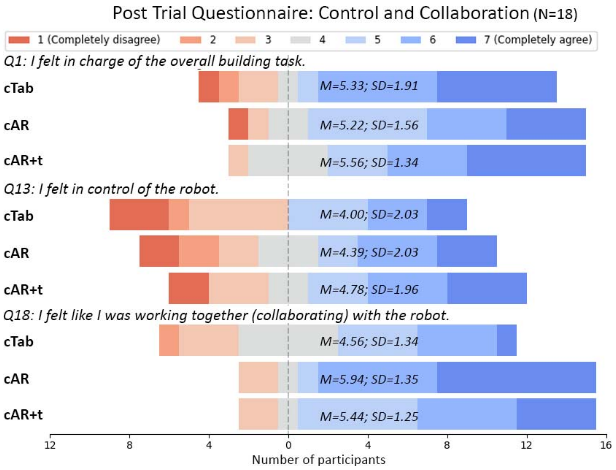


Figure 7: The questions from post-trail questionnaire were rated for **cTab**, **cAR**, and **cAR+t**.

bar), indicating that the robot was not actively stopped by the participant. The green bars show that participants worked on their tasks in parallel and completed these independently of the robot. Further, in most cases, tasks were distributed evenly throughout the assembly procedure.

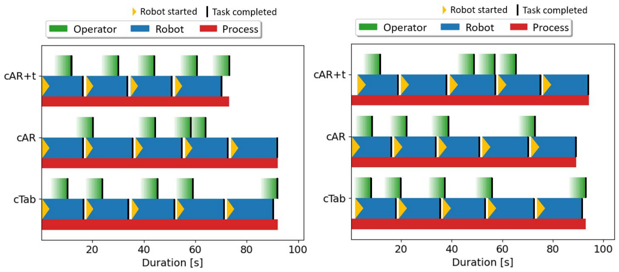


Figure 8: These timelines from two random samples (left: P9, right: P13) show active working times of the participant and robot on their respective tasks in each of the conditions. Robot activity is represented by blue bars, with the start and end of a task indicated by a yellow arrow and black line respectively. The fade-in of green bars indicates the estimated start time of the participant, and again a black line shows task completion. Such plots were analyzed for all participants.

Video analysis further reveals that the interactions between the participant and robot mostly followed a rhythm: while the robot was in the process of picking up a brick, the participant would place one, then the participant would monitor the overall procedure and determine their next steps while the robot would finalize its task. In multiple instances, the participant was faster and thus had to wait for the robot to complete its task before being able to proceed.

Analysis of recordings further revealed that when the participant and robot were to place a brick simultaneously, the participants would wait for the robot when using the **cTab**. But when using the **cAR** (**cAR** + **cAR+t**), they would immediately complete their task. Interestingly, we found no significant difference in task completion time across conditions.

5.1.2 AR is helpful to determine the status of the robot

As can be seen in Fig. 9, participants generally found the AR interface helpful in determining the status of the robot (Q9), they found the path visualization useful (Q10), and it helped them to determine the robot's next actions (Q11). A further indicator for determining the usefulness of the **cAR** could be the number of occurrences when the participants and robot were simultaneously active in the work area. We found a total of 21 such occurrences, i.e. both were about to place a brick. Counting these per condition, we observed notably less simultaneous activity with **cTab**(3 occurrences), compared to **cAR** (18 occurrences; **cAR**: 6 + **cAR+t**: 12). This indicates that participants were more likely to work close to the robot when situated robot status visualizations were available.

We occasionally observed that participants moved a DUPLO brick from one hand to the other before placing it. We learned in interviews that this was done to prevent collision with the robot that was simultaneously moving in the task space. The path visualization was mentioned as helpful for planning the action, preventing alternative strategies, such as pausing the robot, or waiting for it to finish.

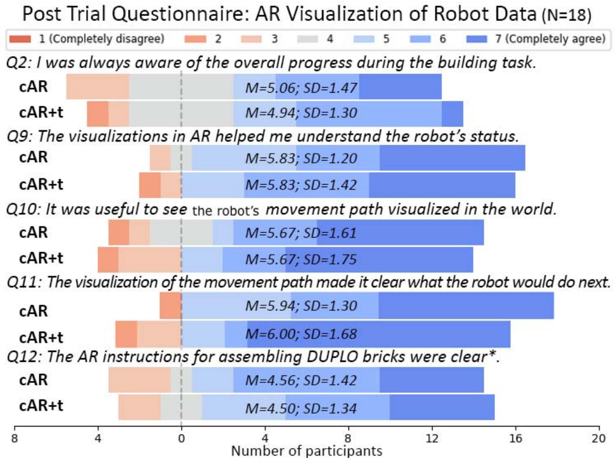


Figure 9: These questions from post-trial questionnaire were rated for **cAR** and **cAR+t**. *Note: to aid understanding here the scores for Q12 are inverted and the statement is positive.

5.2 Task allocation: share equally or all by myself

The third condition (**cAR+t**) gave participants an opportunity to redistribute tasks between themselves and the robot, to investigate the usefulness and usability of the *task list*. They were allowed to modify the playlist at any point during the assembly procedure and could make use of the pause function to gain time for this. Due to the counterbalanced order of conditions, participants completed this task either with *C1*, *C2*, or *C3* (see Fig. 6). Each of these constructions involves 4 yellow bricks that could be placed by either agent. By default, these exchangeable tasks were fairly split between the robot and the participant, i.e., 2 yellow bricks each.

Most participants (12 out of 18) reassigned at least one task and almost all did this before completing their own first task. One participant forms the exception, as they also reassigned a task during the task. Looking at how the participants reassigned tasks, two strategies emerge: "all by myself" and "I do left, you do right", as 6 participants chose to reassign as much as possible to themselves and 4 participants tried to divide the tasks equally while dividing up the workspace. As a side-effect of robot operation speed, participants who reassigned more tasks to themselves were generally faster to complete the assembly sequence.

A section of the post-trial questionnaire (Q6-Q8) was dedicated explicitly to evaluating task allocation through the *task list* in the **cAR+t** condition. The results illustrated in Fig. 10 reveal that most participants felt it clear which tasks could be delegated (Q6) and they were also able to understand the sequence and organize tasks in the form of a "*task list*" (Q8). While most participants found it easy to reassign tasks through the AR interface (Q7), some disagreed strongly with this statement. The interviews may shed light on reasons for such ratings, as some participants reported difficulties in interacting with the buttons of the AR menu (Fig. 4).

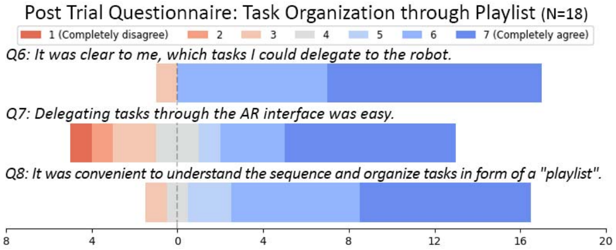


Figure 10: Questions 6-8 from the post-trial questionnaire referring to task scheduling were rated only in *AR Interface w. Task Allocation*. Most participants found the task structure clear (Q6), easy to use (Q7) and the *task list* convenient (Q8).

5.3 Step-by-step instructions in AR

The situated AR instructions for assembly were predominantly perceived as clear (Q12), see Fig. 9.Across all conditions instructions were easy to understand (Q4; **cTab**: $mean = 6.28, SD = 1.13$, **cAR**: $mean = 5.78, SD = 1.31$, **cAR+t**: $mean = 5.5, SD = 1.65$; **cTab** vs. **cAR**: $p = .21$; **cAR** vs. **cAR+t**: $p = 5.87$). Measures of task completion time and observation of participants support that there was no difference between the 2D instructions on the tablet (**cTab**) or the 3D hologram (**cAR**) with regard to supporting the task.

However, across all conditions, the results of the NASA TLX questionnaire [23] found comparable indications of Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration (no significant effects). The only significant effect was found regarding Eye Fatigue, which was significantly higher for the **cAR** compared to the **cTab**(**cTab**: $mean = 1.17, SD = 0.38$, **cAR**: $mean = 2.89, SD = 1.71$; **cTab** vs. **cAR**: $p < .01$; correction for multiple comparisons: $\alpha = 0.025$).

5.3.1 Breakdowns: accidentally doing the work of others

Video analysis revealed three main user errors: (a) doing a task that is assigned to the robot, (b) wrongly positioning a part, and (c) marking a task as complete without doing it.

Error type (a) was counted 3 times in **cTab** while 3 were recovered (i.e. the participant was able to correct the error before a subsequent task failed), and 5 errors occurred for the *AR Interface* (with task allocation) while 2 were recovered. A more detailed investigation into errors where the participant did a robot task (a), revealed that in 3 out of 3 instances for the tablet, and 3 out of 5 instances for the AR interface, the participant actually had an assigned task with the same type of brick (e.g., an orange brick) and apparently confused the two. Furthermore, in three instances where the **cAR** was used, a path visualization was active that indicated the robot was placing that particular brick, which should have provided an additional clue for preventing the error. Error type (b) happened 2 times for **cTab** with none recovered, and 3 errors times for **cAR** with 2 recoveries. Lastly, error type (c) happened only once for **cAR** without recovery.

6 DISCUSSION

Based on the evaluation presented in this paper, we will discuss 1) that participants seem to be more inclined to work simultaneously with the robot when using AR (working in parallel). Based on this, we propose design guidelines for how and when robot intent should be communicated. 2) the strategies for (dynamic) task allocation: "All by myself" or "I do left, you do right". Here we propose further research on user preferences regarding task allocation. 3) general findings when using AR to support human-robot collaboration. In this context, we encourage further exploration of multi-modal interaction to limit context switches and ensure an enjoyable user experience. Lastly, we reflect on the limitations of the user study.

6.1 Supporting operators' awareness of the robot status

We explored two methods of communicating the robot's intent: path visualization (Fig. 4) and holograms (Fig. 5). Based on previous work, e.g., [22, 48, 52], we expected that visual feedback of the planned robot movement would support the operator's situational awareness. This seems confirmed by our evidence from questionnaires, observation and interviews, as it allowed participants to better coordinate their movements and manipulations with respect to the robot. For example, when using **cTab**, participants frequently completed their own task only when the robot had finished its last action. In contrast, this need to wait for their "turn" to manipulate objects in the joint workspace was not apparent with **cAR**, and analysis of video recordings confirms more frequent simultaneous activity. Arguably, the path visualization made the participant more aware of the robot's action and more confident in concluding their own part.

Importantly, it should be noted that we investigated only one type of path visualization and think that more exploration is needed, as different contexts might call for different granularity of visualizations. For example, in some scenarios it may be more beneficial to visualize just parts of the path or the robot, to address potential limitations of visual clutter, cognitive load, etc. Variations have been explored in [10, 22], but comparison and scenario-dependent design guidelines appear to be missing.

Interestingly, some participants indicated that they did not actually need to pay much attention to the path visualization during the study trials. A contributing factor for this may be the information already conveyed through holograms and the predictability of the robot, which made it easy for participants to determine what would happen next. While we think it reasonable that this would change in a longer or more complex task, future work should explore whether predictability makes path visualizations redundant or even detrimental (e.g., due to visual clutter and system complexity).

Related to the predictability of robot movements, some participants remarked that the robot moved quite *organically* or almost human-like. This is an interesting avenue for research [6, 20], and may in future revealwhether more *organic* or *natural* movements increase the operator's willingness to collaborate closely with the robot.

Finally, apart from providing information about the robot's intention, the presented holograms also effectively guided participants in the assembly task, which was described as useful. In comparison to the image-based instructions on the **cTab**, situated visualizations provide the benefit of revealing needed changes in the actual workspace, where unexpected discrepancies or issues can become obvious. However, the holograms likely also caused the majority of user errors and breakdowns (Section 5.3.1). For example, insufficient tracking accuracy of the **cAR** could lead to misalignment of holograms. Further, some participants accidentally completed tasks that were assigned to the robot. Here the path visualization may have provided helpful additional clues that in three instances potentially led to the recovery from such errors in **cAR**. However, on three other occasions, the error was not corrected despite path visualization, indicating that its saliency may be insufficient. This suggests the need to enhance the distinction between an operator and robot assigned task. Here, an advantage of the **cTab** is the possibility to compare the current actual build with an illustration of what is supposed to be built. Thus, supporting this in AR would be interesting. However, here the challenge of occlusion must be addressed as the operator must see both the real and the overlaid virtual object at the same time.

6.2 Task allocation: interface and strategies

With our proposed scheduling interface (*task list*), we aimed to enable novices to effectively plan and coordinate tasks of an assembly procedure between a robot and a human. Overall, our findings support that the *task list* was well understood, supported inspection of the overall assembly sequence and enabled participants to reassign tasks as well as undo reassignments. Importantly, the *task list* clearly revealed the required order of operations and which operations could be completed by each of the agents. However, some participants mentioned that a flat list does not convey parallel operations well. Further, some participants reported difficulties with manipulating the buttons on the AR menu, which is a well-known challenge of mid-air interaction and could be addressed by supporting ray-casting.

The results of our evaluation found two primary strategies for task allocation: "all by myself" and "I do left, you do right". These suggest two user preferences, which, to our knowledge, need further exploration. Firstly, the "all by myself"-strategy might suggest that some participants did not want to twiddle their thumbs while the robot was in progress, as the robot takes comparatively long to complete tasks due to its slow movement speeds. This may have been a strong factor motivating their task assignment choices. Should this be the case, HRC systems, and their task allocation strategies, should ensure that work can be done in parallel, but also prefer a busy operator. Secondly, task allocation strategies should investigate how tasks can be allocated automatically based on territories or zones, such that the human and the robot interfere less with each other. This has to some extent been explored by Mahadevan et al. [34]. Compared to most related work that typically focuses on completion time [27,45,53] and ergonomics [16,31], task allocation should also attempt to include user preference and territoriality.

A limitation that should be noted, is that our study tasks may have offered few options for task reassignment: only four elements could be assigned to either agent, and there was no strict need to update the strategy during the assembly sequence. Thus, the study did not explore the dynamic task allocation to its fullest.

6.3 Using AR to collaborate with a robot

The results showed that the participants generally found the **cAR** easy to use and understand. However, reported issues and observations of user interactions provide some directions for future exploration. As previously mentioned, utilizing hand tracking with the HoloLens 2 for button interaction and scrolling in mid-air turned out to be a challenge. Pilot studies revealed that this issue could to some degree be compensated by extended training of the mid-air interaction technique in the user study. In future work, such issues could be alleviated by supporting different interaction techniques (e.g., ray casting) or other modalities, such as eye-tracking. In the future, we aim to explore additional input modalities, such as voice [3,32] and gaze-based interaction [34], instead of the potentially fatiguing mid-air interaction. Alternatively, a more sophisticated system might explore auto-complete functionality, such that it automatically detects and registers when a task is completed. By thereby limiting the required interaction frequency with the *task list*, context switches, which we already see reduced in **cTab** (i.e., gaze back and forth between tablet and workspace), can be avoided even further.

As expected, the perceived eye fatigue was higher when using the **cAR**, as the HMD (HoloLens2). However, no increase in mental demand or frustration was observed, despite the discomfort and above-mentioned challenges of menu interaction. Other studies have found lower mental demand for AR systems in a robotics context have been found [50].

While our findings indicate that our design of the *task list* interface was useful and easy to understand, when explicitly asked about the playlist metaphor in the interview, the participants explained that the metaphor did not work due to the lack of a progress bar, tasks not disappearing after being completed, and the possibility of some tasks being done in parallel whereas a music playlist is always sequential. One participant mentioned that a better metaphor might be that of composing music, where individual members of the "band" work on their tracks in parallel and collectively produce a final product when all their efforts are combined. These comments provide valuable input for refining our design in the future.

While we have explored two distinct interfaces (AR and tablet) to support HRC, multimodal interfaces [3] may offer further benefits. In this regard, hybrid user interfaces [18] offer an interesting avenue for future research.

6.4 Shortcomings of the Evaluation Scenario

Our presented system was evaluated in a lab study, involving an abstract artificial assembly task that permitted the exploration of the system. While this simplistic assembly task aimed to minimize the risk of confounding factors, it may be argued that the abstract scenario limits the validity of our study. For example, that the overall number of errors was so low, may be attributed to the simplicity of the task and the ability to identify correct placement by counting the knobs on the DUPLO bricks. Indeed, an extensive field study, involving a real assembly task and domain experts, is needed to confirm the findings and may reveal further challenges and unexpected findings. This is a task for future work, for which our work and findings provide a basis.

The study did not have a condition where the tasks should be completed in sequential order, which would have been beneficial to establish an estimate of whether the task execution was faster compared to the parallel approach. However, as speed was not a primary objective of the exploration and the results confirm that parallel work was happening, it is not considered a major issue.

A limitation of the AR interface is the current use of a menu, where the operator needs to split their attention between the list and the workspace (similar to the tablet). A potential solution could be to replace the list with in-situ objects that are interactable. Besides, this may also be a reason behind the absence of differences in task performance between the AR-based interface and the tablet interface.

Finally, our evaluation is limited by our narrow participant sample, skewing towards male participants with prior VR and AR experience. The main reason for this was the limited availability of study participants at the time of evaluation, which took place under restrictions of the COVID-19 pandemic. A follow-up study will need to investigate the generalizability of our findings to the target domain of assembly tasks completed by professionals in the manufacturing industry.

7 CONCLUSION

In this paper, we proposed, built, and evaluated an AR interface supporting collaboration between a human operator and a robot for assembly tasks. We present an AR interface that supports parallel execution of tasks and allows for reassigning tasks to the robot or the operator. Further, we designed situated building instructions in the form of holograms and informed the operator about the robot's status by visualizing the robot's movement path through the workspace. We evaluated our *AR Interface* in comparison to a state-of-the-art 2D control panel on a touchscreen device (*Tablet Interface*) in a user study with 18 participants. Our findings confirm that our AR interface can successfully support operators in coordinating and performing assembly tasks in parallel with a robot. In particular, the situated visualization of the robot's movement path and holographic building instructions were effective in supporting workspace awareness, confidence, and perceived control. Furthermore, by analyzing the participant's interaction with the system, we found two strategies for task allocation: "All by myself" or "I do left, you do right" Our research thereby provides a basis for future work to build on for supporting parallel and interdependent execution of tasks between humans and robots.

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