2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
October 25-29, 2020, Las Vegas, NV, USA (Virtual)

An Augmented Reality Human-Robot Physical Collaboration Interface Design for Shared, Large-Scale, Labour-Intensive Manufacturing Tasks

Wesley P. Chan[1], Geoffrey Hanks[2], Maram Sakr[1,2], Tiger Zuo[2],
H.F. Machiel Van der Loos[2], and Elizabeth Croft[1]

2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) | 978-1-7281-6212-6/20/$31.00 ©2020 IEEE | DOI: 10.1109/IROS45743.2020.9341119

***Abstract*— This paper investigate potential use of augmented reality (AR) for physical human-robot collaboration in large-scale, labour-intensive manufacturing tasks. While it has been shown that use of AR can help increase task efficiency in teleoperative and robot programming tasks involving smaller-scale robots, its use for physical human-robot collaboration in shared workspaces and large-scale manufacturing tasks have not been well-studied. With the eventual goal of applying our AR system to collaborative aircraft body manufacturing, we compare in a user study the use of an AR interface we developed with a standard joystick for human robot collaboration in an experiment task simulating industrial carbon-fibre-reinforced-polymer manufacturing procedure. Results show that use of AR yields reduced task time and physical demand, with increased robot utilization.**

I. BACKGROUND AND MOTIVATION

Robotics and automation in manufacturing has brought tremendous productivity improvements. Yet, many processes have not been automated due to their inherent complexity and variability. Such tasks often require human cognitive capabilities, dexterity, expertise, and flexibility unmatched by current robot technologies. To increase productivity in these processes, robots have been introduced as assistive partners to collaborate with human workers. However, such efforts have had limited success, as current interfaces for industrial robots (teach pendants and computer consoles [1]) are complex, constraining, unintuitive, and unsuitable for on-the-fly interaction. Such complex interfaces hinder performance, discourage use of the robotic assistant, and distract user attention from the task.

One specific class of tasks that can especially benefit from robotic assistants is large-scale, labour-intensive manufacturing procedures. Such procedures involve large workpieces and high physical demand, requiring workers to move and work around the workpiece. A prime example of such tasks is the pleating process in carbon-fibre-reinforced-polymer (CFRP) production for aircraft bodies, as is being tested at the Augsburg facility of our collaborator, the German Aerospace Centre (DLR). This task is labour-intensive as workpieces can reach 4 m in diameter or larger, and workers need to climb over scaffolds to reach all parts of the workpiece (Fig. 1A). To alleviate workers from high physical demands and increase task efficiency and repeatability, large-scale robots are proposed to operate as assistants to workers (Fig. 1B). As these robots are more than six times human size and power, alternate programming methods such as kinesthetic teaching [2] become infeasible due to safety issues. To enable utilization and unlock potential benefits of such robots, an interface allowing workers who are non-robotics experts to intuitively and safely collaborate with such systems is needed.

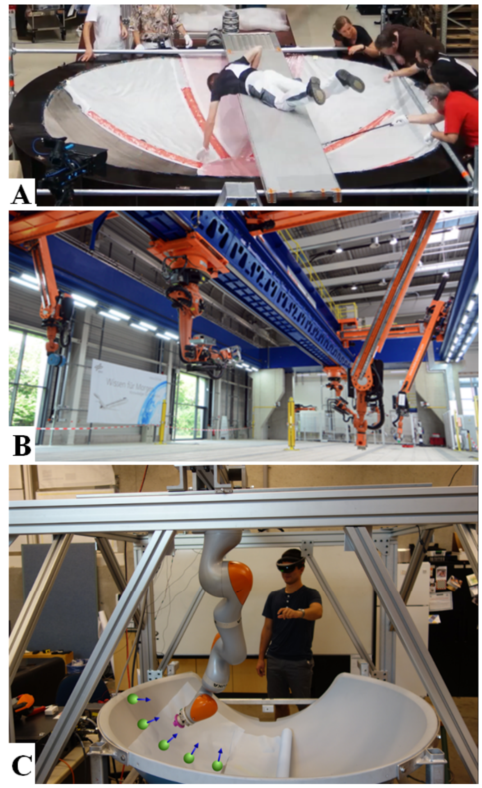

Fig. 1. A - Pleating procedure in CFRP manufacturing. B - DLR's factory in Augsburg with large ceiling-hanging robots. (Images from DLR.) C - Robot setup in the lab. User interacting with robot through our AR system.

Recently, augmented reality (AR) has become a promising alternative for creating intuitive robot interfaces. AR allows rendering of virtual objects and creating of visual user interfaces in the same physical workspace as the robot. Such interfaces allow users to command and interact with robots intuitively through natural gestures and speech, while maintaining focus on the actual robot and task. Herein, we present a study on the use of an AR system that allows users to intuitively instruct and collaborate with an industrial robot. We investigate use of AR and its potential application for human-robot collaboration in an experiment task simulating CFRP manufacturing.

II. RELATED WORK

Recent research has applied AR to many applications including training [3], maintenance [4], and repair [5], and have had positive outcomes. This section provides a review of studies pertaining to the use of AR for robotics.

[1]Monash University, [2]University of British Columbia

A. AR Robot Surrogates

In one of the earliest robotics applications, Chong et al. presented an AR robot guiding system where users interact with a virtual robot to control a real robot [6]. Fang et al. also created a system using AR that allows users to program a robot by moving a virtual robot displayed on a monitor [7]. However, they found that depth perception is reduced and the monitor distracts user focus from the task. Recently, Walker et al. created a drone control system using AR virtual surrogates of the robots [8]. They found that their AR system reduces completion time and perceived stress levels. These systems mainly utilize AR to create a virtual copy of the robot as a proxy for interaction to control the real robot.

B. AR as In-Situ Displays

Andersen et al. used projection AR for visualizing robot and task information in the context of car door assembly [9]. Ro et al. presented a robot that projects arrows onto the floor to direct users [10]. Lim et al. combined the use of a projector and smart phone to enhance user-immersion in a mini-car driving scenario [11]. Kemmoku and Komuro constructed a head-mounted projector AR interface for applications requiring a larger effective display area [12]. However, projected AR suffers from occlusions by users and objects in the environment, and is not the best choice for scenarios involving physical human-robot collaboration. Using a head-mounted AR system to avoid occlusion problems, Hanson et al. compared the use of AR as an instructing interface for an assembly task and found that AR interfaces yield higher efficiency and accuracy [13]. Their study, however, did not involve robots. While these studies focused on using AR as a tool for communicating information to the user, they did not facilitate physical interaction or collaboration with robots.

C. AR for Teleoperation and Programming

Most existing research on the use of AR for human-robot interaction utilizes AR as an interface for teleoperation or programming. Ni et al. created a teleoperation system using AR together with a haptic device for welding tasks [14]. Stadler et al. conducted a workload analysis on industrial robot programmers controlling a robot using tablet-based AR and found that it decreases mental demand but increases completion time [15]. However, the study used a miniature spherical robot (Sphero). Previously, we presented an AR-based system for programming, previewing, and editing robot trajectories and tested it on a human-scale robotic arm. Contrary to the results of Stadler et al., we found that the use of AR reduces robot teaching time but increases mental demand [16]. Similarly, Ong et al. and Frank et al. found that the use of AR for programming table-top robots is more intuitive and efficient [17], [18]. The contradicting results from these studies seem to suggest that robot size and task type may affect the performance of AR-based interfaces.

While existing works have demonstrated AR's potential in increasing task efficiency in different robotics applications, most have focused on robot control, teleoperation, or programming, and on table-top scale robots and tasks, where the user mainly interacts with AR objects in virtual space, and only the robot works in the physical workspace. There have not been studies on the use of AR for tasks requiring both human and robot to physically collaborate in the same workspace, working on a shared physical object simultaneously, or involving larger-scale robots. As human-robot collaboration in shared physical workspace is of particular relevance and interest to industrial tasks (e.g., assembly [19]), we conducted a study on the use of AR for a shared physical workspace collaborative task to evaluate its performance.

III. OBJECTIVE

The objective of our current study is to investigate the potential of using AR to provide an effective, intuitive interface for human-robot collaboration aimed at large-scale, labour-intensive manufacturing tasks, where robot and human need to work simultaneously in the same physical workspace, such as CFRP manufacturing (Fig. 1A). The research questions we seek to answer in this particular context are:

- Can an AR-based interface for collaboration help increase overall task efficiency?
- How does an AR-based interface affect the perceived task workload?
- Can an AR-based interface help encourage and promote human-robot collaboration and robot utilization?

To answer these questions, we compare the use of an AR system we built with a standard joystick-based system in a experiment task simulating CFRP manufacturing.

IV. SYSTEM

A. Robot Platform

Our robot platform comprises a KUKA IIWA LBR14 robot mounted on a two-axis robotic test bench (Fig. 1C). Our robot setup is approximately 1.8 m x 1.7 m x 1.9 m. This mimics the proposed setup using the robots shown in Fig. 1B. At DLR's facility, a LBR14 will be mounted at the end of one of the large robot arms hanging from the ceiling. The ceiling-mounted arm will be used for positioning the LBR14, while the LBR14 will be used for performing the task in collaboration with the human worker. In our setup, the two-axis movable platform serves to position the robot, while the LBR14 executes the task in collaboration with the user (Fig. 2A). The LBR14 is capable of impedance control for safe physical interaction. We used a simple spring-loaded attachment to hold the tool (a marker pen) in our study for passive compliance to limit contact forces and provide safe control and interaction.

B. AR Interface for Human-Robot Collaboration

Our AR system, implemented on a Microsoft HoloLens [20], allows users to collaborate with and instruct the robot through natural speech, gestures, and gaze. An AR marker placed at a known location is used to calibrate the position of the AR system. A virtual model of the robot and work surface is rendered to provide visual feedback of the positional calibration and true context of use - since workpieces may change over the course of task (Fig. 2B). As the user moves

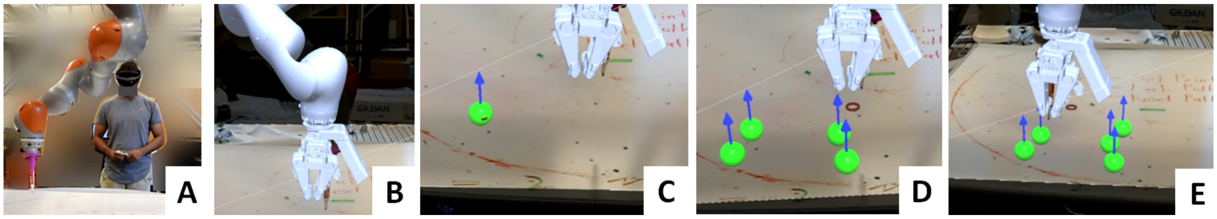

Fig. 2. A - User collaborates with our robot through our AR interface. B - A geometrically accurate model of the robot is rendered over the real robot and displayed to the user. C - User sets a way point through gaze and speech. D - multiple way points are set to define a path. E - the user commands the robot to execute the set path with a speech command.

around the workspace, drift in HoloLens' motion tracking may cause misalignment between virtual and real robot. The user can use the AR marker to recalibrate the AR system any time. The virtual robot mimics motion of the real robot and can be used to provide trajectory preview to the user. The HoloLens recognizes user hand gestures, speech, and gaze, allowing interaction through these channels with the system.

To create a trajectory for the robot, the user looks at a point on the work surface and says the command "set point" to set a way point. A ray is cast from the user's head orientation, and the intersecting point with the work surface is computed. A virtual sphere is rendered at the intersecting point, with an arrow indicating the surface normal, to show the user where the trajectory points are (Fig. 2C). The user can set multiple way points by repeating the "set point" command while looking at each trajectory way point (Fig. 2D). At any time, the user can say the "reset path" command to clear any set way points. After the way points are set, by saying the "lock path" command, the trajectory points are sent to the control computer, which then plans the trajectory, and sends the motion commands to the robot for executing the trajectory (Fig. 2E). A block diagram of our AR and robot control system is shown in Fig. 3.

C. Joystick Trajectory Programming Interface

To allow comparison of our AR interface with a standard industry interface, i.e,. a teach pendant [1], we also implemented a joystick interface using a standard PS3 joystick, mimicking the functionalities provided by teach pendants: To program a robot trajectory, the user pushes the left joystick up/down, left/right to move and position the real robot end effector forward/backward, left/right. Pressing one button saves the current end effector position as a trajectory way point, while pressing another button sends the saved way points to the control computer for trajectory planning and robot execution. Pressing the clear button clears all saved points and resets the trajectory.

V. EXPERIMENT

A. Experiment Task

To test our AR system for human-robot collaboration prior to moving to the large factory robots and the real manufacturing task, we conducted a user interface study in which participants performed an experiment task analogous to the CFRP pleating task [1]. We used a large enough mould (diameter=1.6 m, depth=0.6 m) such that participants have to move around the mould to reach all edges and climb on scaffolds to reach the centre, simulating the challenges and physically-demanding nature of the real task. A pleating task involves two main steps:

1) Create pleats around the mould edges by gathering excess material and folding them neatly.
2) Move and position each pleat along stringers that run from the mould edge to the centre.

The real pleating task requires skill and experience in manipulating the material and is performed by expert workers in the factory. To create an analogue for our participants, we asked them to colour with a marker predefined lines on a whiteboard laid over the mould instead. Step 1 is a more dexterously demanding task, and is simulated by asking participants to colour in zig-zag lines around the edges of the mould (edge path). Step 2 requires movement across large areas of the mould and reaching to the central parts of the mould. Step 2 is simulated by asking participants to colour in lines that run from the edge of the mould to the centre of the mould (center path). To simulate, safely, the need of using scaffolds to reach the mould center, we asked participants to set up a small scaffold next to the mould and use it as a stepping stool whenever they need to reach and perform the centre tasks. In all, our experimental task consists of 4 sets of pleating paths (edge path + centre path) to be executed in a given order. In the real task, the vacuum tubing needs to be assembled and placed under the plastic layer. In our simulated task, we also asked the participants to assemble the actual tubing as the last part of the simulated task.

B. Experiment Conditions

In our experiment, we tested five conditions:

Human Condition (H). Participant performs the task alone. This simulates the current manual CFRP part fabrication as a baseline.

Joystick Condition - Task Division Predefined (J1). Participant performs task in collaboration with robot using joystick interface (analogous to teach pendant programming). Participant is instructed to complete edge paths, while using robot to help complete centre paths. This represents the intended use case, where the robot is used to help complete the most labour-intensive and hard-to-reach task components.

AR Condition - Task Division Predefined (AR1). Participant performs task in collaboration with robot using AR interface. Participant is instructed to complete edge paths, while using robot to help complete centre paths. Again, this represents the intended use case.

[1]demo video: https://youtu.be/22CNBTle1Dw

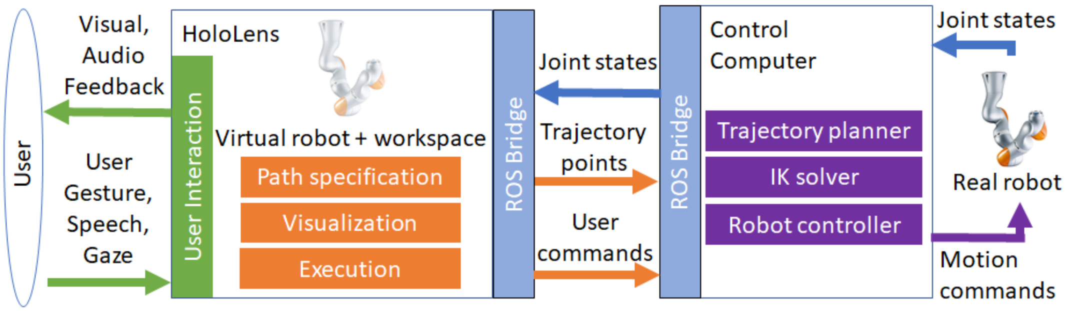

Fig. 3. System block diagram - User interacts with HoloLens through gesture, speech, and gaze, while visual and audio feedback can be provided. Our AR interface provides path specification, visualization, and execution functionalities. The HoloLens communicates with control computer using ROS Bridge [21]. The control computer commands robot using motion planner library MoveIt [22]. The real robot continuously sends current joint states to control computer, which then sends it to HoloLens for visual display as feedback to user.

Joystick Condition - Task Division Unspecified (J2). Participant performs task in collaboration with robot using joystick interface. Participant is given freedom to decide which parts of the task to complete by him/herself, and which parts to enlist robot to help complete. This tests how much user would choose to utilize robot given joystick interface.

AR Condition - Task Division Unspecified (AR2). Participant performs task in collaboration with robot using AR interface. Participant is given freedom to decide which parts of the task to complete him/herself, and which parts to use robot to help complete. This tests how much user would choose to utilize the robot given our AR interface.

C. Experiment Procedure

We first provide an overview of the pleating task and explain our experiment task and procedure to each participant. We then introduce the joystick and AR interfaces, and let participants try out the interfaces to become familiarized with them. After that we begin the experimental trials.

Each participant performs the simulated pleating task once in each condition. The first condition is always H to allow participant to first understand and complete the entire task. The second and third trials are J1 and AR1, with ordering counter-balanced to mitigate carryover effects. The last two trials are J2 and AR2, again with ordering counter-balanced. After each condition, participant completed the NASA-TLX questionnaire [23]. At the end of the experiment, we also ask participants for any additional comments they have.

We recruited 10 participants (9 male, 1 female) for the experiment via social media, word of mouth, and posters posted on the University of British Columbia campus. The experiment was approved by the UBC Behavioural Research Ethics Board (ethics approval application ID: H10-00503).

D. Hypotheses

We formulated the following hypotheses:

- **H1**: The use of a robot assistant (J1, AR1, J2, AR2) reduces task completion time and physical load when compared to the human-only condition (H).
- **H2**: The use of AR (AR1, AR2) compared to joystick (J1, J2) reduces completion time and task load on users.
- **H3**: The use of AR (AR2) promotes collaboration and results in increased robot utilization.

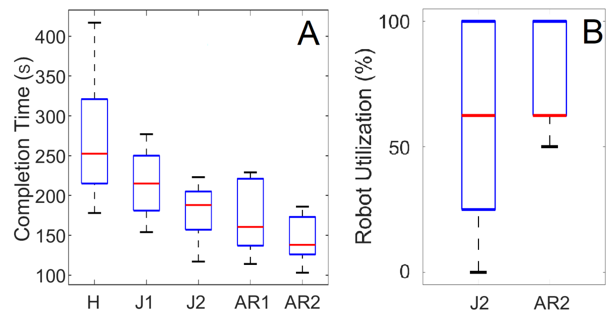

Fig. 4. A. Measured completion time, t. B. Measured robot Utilization, R.

VI. ANALYSIS

We measured completion time, t, in each condition, and robot utilization, R, in J2 and AR2, calculated as the percentage of paths (edge or centre) participant chose to execute using the robot out of all paths. A t-test was used to determine if robot utilization increased in J2 and AR2, compared to when the task division was specified in J1 and AR1 (at 50%). Following existing works [15], [16], [24], ANOVA followed by paired t-tests with Bonferroni-Holm method was performed to identify significant difference in t and the TLX results ($\alpha = 0.05$). All data passed the Anderson-Darling normality test.

VII. RESULTS

A. Completion Time

Measured completion time, t, is shown in Fig. 4A and Table I. AR1 and AR2 achieved shortest t compared to H, J1 and J2. ANOVA indicated significant difference among t ($F(4,45) = 9.96, p < 0.001$), while pairwise t-test showed that t in J1, J2, AR1, and AR2 are significantly shorter than in H ($t(9) = 3.50, p = 0.007$; $t(9) = 4.87, p < 0.001$; $t(9) = 5.56, p < 0.001$; $t(9) = 5.41, p < 0.001$). Both t in AR1, AR2 are also found to be shorter than those in J1, J2, respectively ($t(9) = 4.27, p = 0.002$; $t(9) = 3.92, p = 0.004$).

TABLE I

COMPLETION TIME, t, MEASURED IN EACH CONDITION.

	H	**J1**	**J2**	**AR1**	**AR2**
t(s)	269 ± 77	213 ± 42	182 ± 34	169 ± 42	145 ± 29

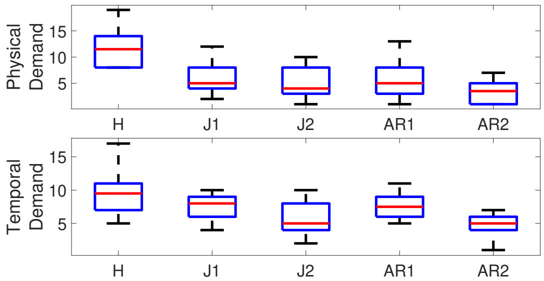

Fig. 5. Participant response to NASA-TLX [23] questions (21 point scale).

TABLE II

NASA-TLX [23] QUESTIONNAIRE RESULTS (21 POINT SCALE).

	H	J1	J2	AR1	AR2
physical demand	11.8±3.8	6.1±3.2	5.1±3.0	5.8±3.7	3.5±2.1
temporal demand	10.1±3.9	7.6±2.1	5.6±2.5	7.4±2.0	4.7±2.0

B. *Task Load*

Overall, AR2 yielded lowest physical demand, temporal demand, effort and frustration among all conditions, while AR1 yielded highest performance and H, lowest mental demand. ANOVA showed significant differences for physical and temporal demand ($F(4,45) = 9.63, p < 0.001$; $F(4,45) = 6.37, p < 0.001$), but not for mental demand, performance, effort, and frustration ($F(4,45) = 0.83, p = 0.513$; $F(4,45) = 0.37, p = 0.831$; $F(4,45) = 2.04, p = 0.104$; $F(4,45) = 1.40, p = 0.250$). Fig. 5 and Table II shows the results for physical and temporal demand for the five conditions. *Post hoc* analysis showed that J1, J2, AR1, and AR2 had significantly lower physical demands compared to H ($t(9) = 4.17, p = 0.002$; $t(9) = 3.91, p = 0.004$; $t(9) = 3.72, p = 0.005$; $t(9) = 5.08, p < 0.001$), and that AR2 also had significantly lower temporal demands compared to H ($t(9) = 4.23, p = 0.002$).

C. *Robot Utilization*

Robot utilization, R, for J2 and AR2 are shown in Fig. 4B. The minimum for J2 is 0% with 4 out of 10 participants measuring 50% or below, meaning some participants decided to use the robot less or not at all given the joystick interface, while the minimum for AR2 is 50%, with all except one participants measuring above 50%, meaning that most participants used the robot for more than half of the task when given the AR interface. Compared to J1 and AR1 (when R fixed at 50%), robot utilization in AR2 was significantly higher ($t(9) = 3.67, p = 0.005$), while in J2, it was not ($t(9) = 1.56, p = 0.153$).

VIII. DISCUSSION

A. *Benefits of a Robotic Assistant*

Results showed that use of a robot assistant regardless of the interface (J1, J2, AR1, AR2) reduces task completion time and physical demand (when compared to H). Thus, our findings support our hypothesis H1. While this result is positive, further long term tasks analysis is needed to eliminate novelty and evaluate learning effects. As the current CFRP manufacturing process is still completely manual, these results are noteworthy since they suggest that introduction of robot assistants could help increase productivity and reduce risk of strain injuries by reducing physical demand.

B. *AR vs Joystick*

Completion time was significantly shorter with AR (AR1, AR2) when compared to joystick (J1, J2 respectively). These results agree with [15], [16], [17], [18]. However, contrary to [15], which found AR decreases mental load, and to [16], which found AR increased mental load and decreased physical load, our results did not show significant differences. This discrepancy is perhaps attributed to the fact that our task and robot are of larger scale and higher physical demand. Thus, we only found support for the first part of hypothesis H2 (completion time would be reduced), but not for the second part (task load would be reduced). On the other hand, load was shown not to be increased by the use of AR either.

C. *Robot Utilization*

The importance of building robotic systems that are accepted and adopted by users has been highlighted by many existing works, as this stimulates further development and use of the technology [25], [26], [27]. Robot utilization, R, measured in J2 and AR2 (when task division was left for users to decide) indicates to what degree users chose to use the robot given the interface. Even though joysticks are more widespread and familiar than AR devices, R was found to be significantly higher in AR2, while in J2, there was no significant difference.

Furthermore, minimum R in J2 was found to be 0%, although completion time, t, in J1 was found to be lower than in H. Thus, with a joystick interface, although participants on average were able to complete the task faster when they were forced to use the robot, given choice, some participants would rather not use the robot at all. This exemplifies a case where, even when the technology is capable, if the interface to the technology is lacking, users may end up abandoning the technology altogether. Our AR interface, on the other hand, only encouraged participants to utilize the robot more (R greater than 50% for 9 out of 10 participants). Our results support our hypothesis H3, demonstrating that our AR interface is effective in promoting human-robot collaboration. Again, while this result is positive, we note that there is a novelty effect with using the AR interface and longer term user studies are warranted.

D. *Participant Comments*

Participants commented positively on our AR system, saying that the interface was ”more convenient”, ”easier”, or ”faster”, and referred to it as ”the best one” out of the three choices of fully manual, joystick, or AR. A few participants commented that using the joystick was slower but more accurate, using the AR interface was harder to locate the waypoints, and the alignment of the virtual and real robots was not as good. Positional accuracy is indeed a common limitation in AR applications. Thus, it may not be the best choice for tasks requiring high positional accuracy. However, for applications that can accommodate or adjust for this shortcoming (such as our target application of pleating in CFRP manufacturing), AR offers many other advantages (as shown by our results). In our envisioned use case, the robot will help gather and pre-position the pleats from hard-to-reach locations (the most labour-intensive part of the current process), while the skilled worker will then perform the final positioning. For one participant, the HoloLens had difficulty recognizing speech commands. As a result, this affected, by about 70%, how much the participant would have used the robot/AR system. Interestingly, this participant still chose to use the robot more than 50% in the AR2 condition.

E. Limitations

The pleating task was replaced with a simpler colouring task in our study so that it could be performed by participants. While this task was designed to reflect key features of the real task, it would be worthwhile to study how task difficulty affects the results. Furthermore, while the robot test bench used in our study is indeed of larger-scale compared to table-top robots used in existing works [15], [16], [17], our target robots in DLR's factory are much larger. Our eventual goal is to test our system using those robots. As previously discussed, novelty effect of both robot and AR may also influence the study results. Longer training periods could be used to reduce this effect. But as workers get more familiarized with the robot and more proficient in using the AR interface, we expect AR-Robot utilization to increase. When setting Way points using head orientation, users' natural head motion may introduce some noise. A filter may be used to reduce this noise. But none of our participants noted this as an issue.

IX. CONCLUSION AND FUTURE WORK

To enable robot assistants to help human workers in large-scale, labour-intensive manufacturing procedures, we have created an AR interface for programming and collaborating with robots. Our user study comparing use of our AR system with current manual method and a standard joystick interface showed that our AR interface has the potential to improve task efficiency and reduce physical load, while promoting robot utilization and human-robot collaboration.

For future work toward applying our AR system in CFRP manufacturing on a pilot basis, we will be investigating use of additional feedback channels for bidirectional human-robot communication such as gestures and haptics. Personalized speech recognition may be implemented to improve user experience and performance. In addition, combined commands has been suggested. We will also explore potential use of our system for other tasks related to CFRP.

X. ACKNOWLEDGEMENT

We thank our collaborators Matthias Beyrle and Jan Faber at DLR for their expert advice on guiding this project.

REFERENCES

[1] B. Daniel, P. Korondi, and T. Thomessen, "New approach for industrial robot controller user interface," in *IECON*, 2013, pp. 7831–7836.
[2] B. Akgun, M. Cakmak, J. W. Yoo, *et al.*, "Trajectories and keyframes for kinesthetic teaching: A human-robot interaction perspective," in *HRI*, 2012, pp. 391–398.
[3] S. Webel, U. Bockholt, T. Engelke, *et al.*, "An augmented reality training platform for assembly and maintenance skills," *Robotics and Autonomous Systems*, vol. 61, no. 4, pp. 398–403, 2013.
[4] T. Engelke, J. Keil, P. Rojtberg, *et al.*, "Content first: a concept for industrial augmented reality maintenance applications using mobile devices," in *ACM Multimedia Systems Conference*, 2015, pp. 105–111.
[5] S. Henderson and S. Feiner, "Exploring the benefits of augmented reality documentation for maintenance and repair," *TVCG*, vol. 17, no. 10, pp. 1355–1368, 2011.
[6] J. Chong, S. Ong, A. Nee, *et al.*, "Robot programming using augmented reality: An interactive method for planning collision-free paths," *Robotics and Computer-Integrated Manufacturing*, vol. 25, no. 3, pp. 689 – 701, 2009.
[7] H. Fang, S. Ong, and A. Nee, "Novel ar-based interface for human-robot interaction and visualization," *Advances in Manufacturing*, vol. 2, no. 4, pp. 275–288, 2014.
[8] M. E. Walker, H. Hedayati, and D. Szafir, "Robot teleoperation with augmented reality virtual surrogates," in *HRI*, 2019, pp. 202–210.
[9] R. S. Andersen, O. Madsen, T. B. Moeslund, *et al.*, "Projecting robot intentions into human environments," in *RO-MAN*, 2016, pp. 294–301.
[10] H. Ro, J. Byun, I. Kim, *et al.*, "Projection-based augmented reality robot prototype with human-awareness," in *HRI*, 2019, pp. 598–599.
[11] C. Lim, J. Choi, J. Park, *et al.*, "Interactive augmented reality system using projector-camera system and smart phone," in *ISCE*, 2015, pp. 1–2.
[12] Y. Kemmoku and T. Komuro, "Ar tabletop interface using a head-mounted projector," in *ISMAR*, 2016, pp. 288–291.
[13] R. Hanson, W. Falkenström, and M. Miettinen, "Augmented reality as a means of conveying picking information in kit preparation for mixed-model assembly," *Computers & Industrial Engineering*, vol. 113, pp. 570–575, 2017.
[14] D. Ni, A. Yew, S. Ong, *et al.*, "Haptic and visual augmented reality interface for programming welding robots," *Advances in Manufacturing*, vol. 5, no. 3, pp. 191–198, 2017.
[15] S. Stadler, K. Kain, M. Giuliani, *et al.*, "Augmented reality for industrial robot programmers: Workload analysis for task-based, augmented reality-supported robot control," in *RO-MAN*, 2016, pp. 179–184.
[16] C. P. Quintero, S. Li, M. K. X. J. Pan, *et al.*, "Robot programming through augmented trajectories in augmented reality," *IROS*, pp. 1838–1844, 2018.
[17] S. Ong, A. Yew, N. Thanigaivel, *et al.*, "Augmented reality-assisted robot programming system for industrial applications," *Robotics and Computer-Integrated Manufacturing*, vol. 61, p. 101820, 2020.
[18] J. A. Frank, M. Moorhead, and V. Kapila, "Realizing mixed-reality environments with tablets for intuitive human-robot collaboration for object manipulation tasks," in *RO-MAN*, 2016, pp. 302–307.
[19] B. Gleeson, K. MacLean, A. Haddadi, *et al.*, "Gestures for industry intuitive human-robot communication from human observation," in *HRI*, 2013, pp. 349–356.
[20] B. C. Kress and W. J. Cummings, "Towards the ultimate mixed reality experience: Hololens display architecture choices," in *SID Symposium Digest of Technical Papers*, vol. 48, no. 1, 2017, pp. 127–131.
[21] "Ros bridge suite," http://wiki.ros.org/rosbridge_suite, 2019.
[22] "Moveit," https://moveit.ros.org/, 2019.
[23] S. G. Hart and L. E. Staveland, "Development of nasa-tlx (task load index): Results of empirical and theoretical research," in *Advances in psychology*. Elsevier, 1988, vol. 52, pp. 139–183.
[24] J. de Winter and D. Dodou, "Five-point likert items: t test versus mann–whitney–wilcoxon," *Practical Assessment, Research and Evaluation*, vol. 15, 2010.
[25] T. Klamer and S. B. Allouch, "Acceptance and use of a social robot by elderly users in a domestic environment," in *International Conference on Pervasive Computing Technologies for Healthcare*, 2010, pp. 1–8.
[26] M. Heerink, B. Krose, V. Evers, *et al.*, "The influence of a robot's social abilities on acceptance by elderly users," in *RO-MAN*, 2006, pp. 521–526.
[27] M. Moradi, M. Moradi, and F. Bayat, "On robot acceptance and adoption a case study," in *Conference of AI Robotics and 10th RoboCup Iran Open International Symposium*, 2018, pp. 21–25.