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AR-based interaction for human-robot collaborative manufacturing

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ABSTRACT

Industrial standards define safety requirements for Human-Robot Collaboration (HRC) in industrial manufacturing. The standards particularly require real-time monitoring and securing of the minimum protective distance between a robot and an operator. This paper proposes a depth-sensor based model for workspace monitoring and an interactive Augmented Reality (AR) User Interface (UI) for safe HRC. The AR UI is implemented on two different hardware: a projector-mirror setup and a wearable AR gear (HoloLens). The workspace model and UIs are evaluated in a realistic diesel engine assembly task. The AR-based interactive UIs provide 21–24% and 57–64% reduction in the task completion and robot idle time, respectively, as compared to a baseline without interaction and workspace sharing. However, user experience assessment reveal that HoloLens based AR is not yet suitable for industrial manufacturing while the projector-mirror setup shows clear improvements in safety and work ergonomics.

1. Introduction

In order to stay competitive, European small and medium-sized enterprises (SMEs) need to embrace flexible automation and robotics, information and communications technologies (ICT) and security to maintain efficiency, flexibility and quality of production in highly volatile environments [1]. Raising the output and efficiency of SMEs will have a significant impact on Europe's manufacturing and employment capacity. Robots are no longer stand-alone systems in the factory floor. Within all areas of robotics, the demand for collaborative and more flexible systems is rising as well [2]. The level of desired collaboration and increased flexibility will only be reached if the systems are developed as a whole including perception, reasoning and physical manipulation. Industrial manufacturing is going through a process of change toward flexible and intelligent manufacturing, the so-called Industry 4.0. Human-robot collaboration (HRC) will have a more prevalent role and this evolution means breaking with the established safety procedures as the separation of workspaces between robot and human operator is removed. However, this will require special care for human safety as the existing industrial standards and practices are based on the principle that operator and robot workspaces are separated and violations between them are monitored.

HRC has been active in the past to realize the future manufacturing expectations and made possible by several research results obtained during the past five to ten years within the robotics and automation scientific communities [3]. In particular, this has involved novel

mechanical designs of lightweight manipulators, such as the Universal Robot family and KUKA LBR iiwa. Due to the lightweight structure, slow speed, internal safety functions and impact detection, the robots are considered a more safe solution for close proximity work than traditional industrial robots. The collaborative robots can be inherently safe, but the robotic task can create safety hazards for instance by including sharp or heavy objects that are carried at high speed. In order to guarantee the safety of the human co-worker, a large variety of external multi-modal sensors (camera, laser, structured light etc.) has been introduced and used in robotics applications to prevent collisions [4,5]. In order to transfer research solutions from the lab to industrial settings they need to comply with strict safety standards. The International Organization for Standardization (ISO) Technical Specification (TS) 15066 [6] addresses in detail the safety with industrial collaborative robotics and defines further four different collaborative scenarios. The first specifies the need and required performance for a safety-rated, monitored stop (robot moving is prevented without an emergency stop conforming to the standard). The second outlines the behaviors expected for hand-guiding a robot's motions via an analog button cell attached to the robot. The third specifies the minimum protective distance between a robot and an operator in the collaborative workspace, below which a safety-rated, controlled stop is issued. The fourth limits the momentum of a robot such that contact with an operator will not result in pain or injury.

The main focus of this work is to define a model to monitor safety margins with a depth sensor and to communicate the margins to the

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Fig. 1. The proposed interactive UIs for safe human-robot manufacturing: a) projector-mirror and b) wearable (AR) HoloLens. Video: <https://youtu.be/-WW0a-LEGLM>.

operator with an interactive User Interface (UI), illustrated in Fig. 1. The work focuses on the third scenario of ISO/TS where the operator-robot distance is communicated interactively.

This paper proposes a shared workspace model for HRC manufacturing and interactive UIs. The model is based on the virtual zones introduced by Bdiwi et al. [7]: robot zone and human zone. In the human zone an operator can freely move and the robot is not allowed to enter. The robot zone is dynamically changing based on robot tasks and if the operator or any other object enters the robot zone, the robot is halted. In the proposed model, the two zones are separated by a safety monitored danger zone and any changes in the workspace model, either from the robot or operator side, cause halting the robot. The purpose of the safety zone is to allow dynamic update of the workspace model without compromising safety. The proposed workspace model, safety monitoring and UIs in the work are consistent with their collaboration levels Level 1 and Level 2 proposed by Bdiwi et al. [7]. The work belongs to the Safety Through Control category. Instead of a passive system this paper proposes a safety model which allows a dynamic AR-based interaction for HRC.

The paper is organized as follows. First, Section 2 describes briefly the background for safe HRC in industrial settings and reviews the current state-of-the-art. Section 3 explains the proposed shared workspace model in detail and in Section 4 two different AR-based UIs integrated to the proposed model are discussed. Next, Section 5 explains the experimental setup for evaluating the workspace model and UIs in a realistic assembly task. Finally, in Section 6 the results from the experiments are reported and conclusions are drawn in Section 7.

2. Related work

2.1. Human-robot collaboration in manufacturing

HRC in manufacturing context aims at creating work environments where humans can work side-by-side with robots in close proximity. In such setup, the main goal is to achieve efficient and high-quality manufacturing processes by combining the best of both worlds: strength, endurance, repeatability and accuracy of robots complemented by the intuition, flexibility and versatile problem solving skills of humans. During a collaboration task, the first priority is to ensure safety of the human co-worker. Vision sensors have been a popular choice to gain information from the surrounding environment, which is crucial for safe trajectory planning and collision avoidance. Other sensing modalities, such as pressure/force, can be combined with visual information to enhance the local safety sensing [8]. In addition to the safety aspect, one of the key challenges in industrial HRC is the interaction and communication between the human and robot resources [9]. According to Liu and Wang [10] the ICT system should be able to provide information feedback and support a worker in the HRC manufacturing. In industrial settings, the physical environment (i.e. floor, tables) can be used as a medium where task-related information,

such as boundaries of the safe working area or user interface components can be projected.

In the literature, several recent works have demonstrated their HRC systems on real industrial manufacturing tasks, where both aspects, safety and communication, are considered. Vogel et al. [11] presented a collaborative screwing application where a projector-camera based system was used to prevent collision and display interaction and safety-related information during the task. In [12] the authors proposed a wearable AR-based interface integrated to an off-the-shelf safety system. The wearable AR supports the operator on the assembly line, by providing virtual instructions on how to execute the current task in the form of textual information or 3D model representation of the parts. The integrated interface in [12] was utilized in an automotive assembly task where a wheel group was installed as a shared task. De Gea Fernández [13] and Magrini [14] fused sensor data from different sources (IMU, RGB-D and laser) and a standardized control and communication architecture was used for safety robot control. Human actions and intentions were recognized through hand gestures and the systems were validated in a real industrial task from the automotive industry. While the mentioned implementations are good examples of safe HRC in manufacturing, the works are mainly technological demonstrations and do not provide data from qualitative or quantitative evaluations that could further emphasize the need of HRC. More similar to this work, a context-aware mixed reality approach was utilized in car door assembly and evaluated against two baseline methods (printed and screen display instructions) [15]. From the experiments, quantitative (efficiency and effectiveness of the task completion) as well as qualitative data (human-robot fluency, trust in robot etc.) were measured through recordings and questionnaires, respectively.

2.2. Safety standards, guidelines and strategies

The manufacturing industry leans on industrial standards that define safety requirements for HRC and, therefore, it is important to reflect research to the existing standards. One of the first attempts to define the work guidelines between human and robot was the ISO 10218-1/2 [16, 17] standards, describing the safety requirements for robot manufacturers and robot system integrators. However, the safety requirements were not comprehensively discussed as the current Industry 4.0 requires more flexible HRC. TS 15066 [6] was introduced to augment the existing standards and for instance added a completely new guideline for the maximum biomedical limits for different human body parts in HRC. The ISO/TS combination defines four techniques for collaborative operation for collaborative applications: *safety-rated monitored stop (SMS)*, *hand-guiding operation (HG)*, *speed and separation monitoring (SSM)* and *power and force limiting (PFL)*.

Recently, several authors have provided design guidelines and concepts corresponding to next-generation manufacturing and aligned with today's safety standards. Marvel [18] proposed a set of metrics to evaluate SSM efficiently in shared workspaces. In contrast, Sloth et al.

[19] estimated the highest velocity a collaborative robot arm can reach, while still complying with PFL. Bdiwi et al. [7] proposed four different levels of interaction in HRC. In the bottom level, the robot and human work inside the same working space but have separate tasks. In the other end, the human and robot have a shared task with physical interaction. In each level, different types of safety functions are developed, linked and analyzed. In this paper the described taxonomies are used as a guideline, defining the safety requirements and standards for the implemented HRC application. In [20, 21], the safety issue was discussed from the perspective when the collision between the human and robot cannot be necessarily avoided. The authors summarized three different strategies for safety: *crash safety* (controlled collision using power/force control), *active safety* (external sensors for collision prediction) and *adaptive safety* (applying corrective actions that lead to collision avoidance). Lasota et al. [22] provided a comprehensive survey of existing safety strategies in HRC and divided the methods into four different directions: *Safety Through Control*, *Safety Through Motion Planning*, *Safety Through Prediction* and *Safety Through Consideration of Psychological Factors*.

2.3. Vision-based safety systems

Safety through control is the most active research field in HRC safety, where the collision is prevented for instance by stopping or slowing down the robot through the use of methods including defining safety regions or tracking separation distance [4]. One of the earliest approaches in industrial environments is to use volumetric virtual zones, where a movement inside a certain zone would signal an emergency stop or slowing down the robot. SafetyEYE (Pilz) [23] and SafeMove (ABB) [24] are few standardized and commercialized vision-based safety systems that use an external tracking system to monitor movement inside predefined safety regions. Similar to the proposed safety system in this paper, the authors [25,26] presented an approach where the regions can be updated during run-time. In [26] a dynamic robot working area is projected on a flat table by a standard digital light processing (DLP) projector and safety violations are detected by multiple RGB cameras that inspect geometric distortions of the projected line due to depth changes. Moreover, recent research [27–29] have discussed an efficient and probabilistic implementation of SSM as dictated by the ISO 15066, where the safety system has dynamic control of the safety distance between the robot and human operator such that it complies with the minimum safety requirements.

Depth sensing has become a popular and efficient approach to monitor the shared environment and to prevent collision between the robot and an unknown object (e.g., a human operator). In most of the approaches a virtual 3D model of the robot is generated and tracked during run-time while real measurements of the human operator from the depth sensor are used to calculate the distance between robot and human body parts. Depth sensing is then combined with reactive and safety-oriented motion planning that guides the manipulator to prevent collisions [30–32]. For a practical application these methods have to be extended to multi-sensor systems where the possibility of having occluded points is removed [33]. Current consumer-grade RGB-D sensors can deliver up to several million point measurements in a second which requires substantial computational power. For real-time interaction more complex implementations have been proposed such as GPU-based processing [34] and efficient data-structures [35]. In contrast, this work combines depth sensing with zone-based separation monitoring (see Section 3), ensuring safe interaction without an expensive feature tracking system and complex implementation of real time motion planning. In [36] a vision-based neural network monitoring system is proposed for locating the human operator and ensuring a minimum safety distance between the co-workers. In parallel, deep models have been proposed for human hand and body posture recognition [37] and intention recognition in manufacturing tasks [38]. However, most of the learning-based approaches assume all human actions to be from a

known observation set and are not designed to work for unseen actions, making them less practical for complex tasks.

2.4. AR-based operator support systems

Advances in display and vision technologies have created new interaction modalities that enable informative and real-time communication in shared workspaces. In robotics, various different signaling techniques have been proposed during the years and one common way is to project 2D information to table or floor [39]. One of the earliest approaches to create a communication interface between robot and human was introduced in [40]. The paper presents a system that visually tracks the operator's pointing hand and projects a mark at the indicated position using an LCD projector. The marker is then utilized by the robot in a pick-and-place task. More recently, Vogel et al. [11] used a projector to create a 2D display with virtual interaction buttons and textual description that allow intuitive communication. In another recent work [15,41] the authors proposed a projector-based display for HRC in industrial car door assembly. In contrast to other projector-based works, the system can display visual cues on complex surfaces. User studies of the systems against two baselines, a monitor display and simple text descriptions, showed clear improvements in terms of effectiveness and user satisfaction. Wearable AR such as head-mounted displays (HMD) and stereoscopic glasses have recently gained momentum as well. Earliest versions of wearable AR devices were typically considered bulky and ergonomically uncomfortable when used over long periods of time [42]. In addition, each of the human participants in the collaborative task is required to wear the physical device. However, 2D displays can only provide limited expression power and can be more easily interfered, for instance, due to direct sunlight or obstructing obstacles. In [43] a HMD was used for robot motion intent communication, which evaluated the method's effectiveness against a 2D display in a simple toy task. Huy et al. [44] demonstrated the use of HMD in an outdoor mobile application where a projector system cannot be used. Elsdon and Demiris [45] introduced a handheld spray robot where the control of the spraying was shared between human and robot. In [12] the authors combined two wearable AR-gear, a head-mounted display and a smartwatch, for supporting operators in shared industrial workplaces.

While the advances of AR technologies have increased their usage in HRC applications, it is unclear how mature the wearable AR gear technology is for real industrial manufacturing. Therefore, this paper investigates HRC safety with two different AR-based UIs, wearable AR and projector-based AR, that are evaluated in a real diesel engine assembly task. The UIs are used together with the proposed safety system that establishes dynamic collaborative zones as defined in Bdiwi [7]. The shared workspace is then modelled and monitored using a single depth sensor installed on the ceiling overseeing all actions in the workspace.

3. The shared workspace model

In the model, a shared workspace S is modelled with a single depth map image I_s and divided to three virtual zones: robot zone Z_r , human zone Z_h and danger zone Z_d (Fig. 2). The zones are modelled by binary masks in the same space as I_s which makes their update, display and monitoring fast and simple. The depth map image I_s is aligned with the robot coordinate system. The robot zone Z_r (blue) is dynamically updated and subtracted from I_s to generate the human zone Z_h (gray). The two zones are separated by the danger zone Z_d (red) which is monitored for safety violations. Changes in Z_h are recorded to binary masks M_i (green). Manipulated objects are automatically added to Z_r , see Fig. 2c.

3.1. Depth-based workspace model

The work considers a shared workspace monitored by a depth

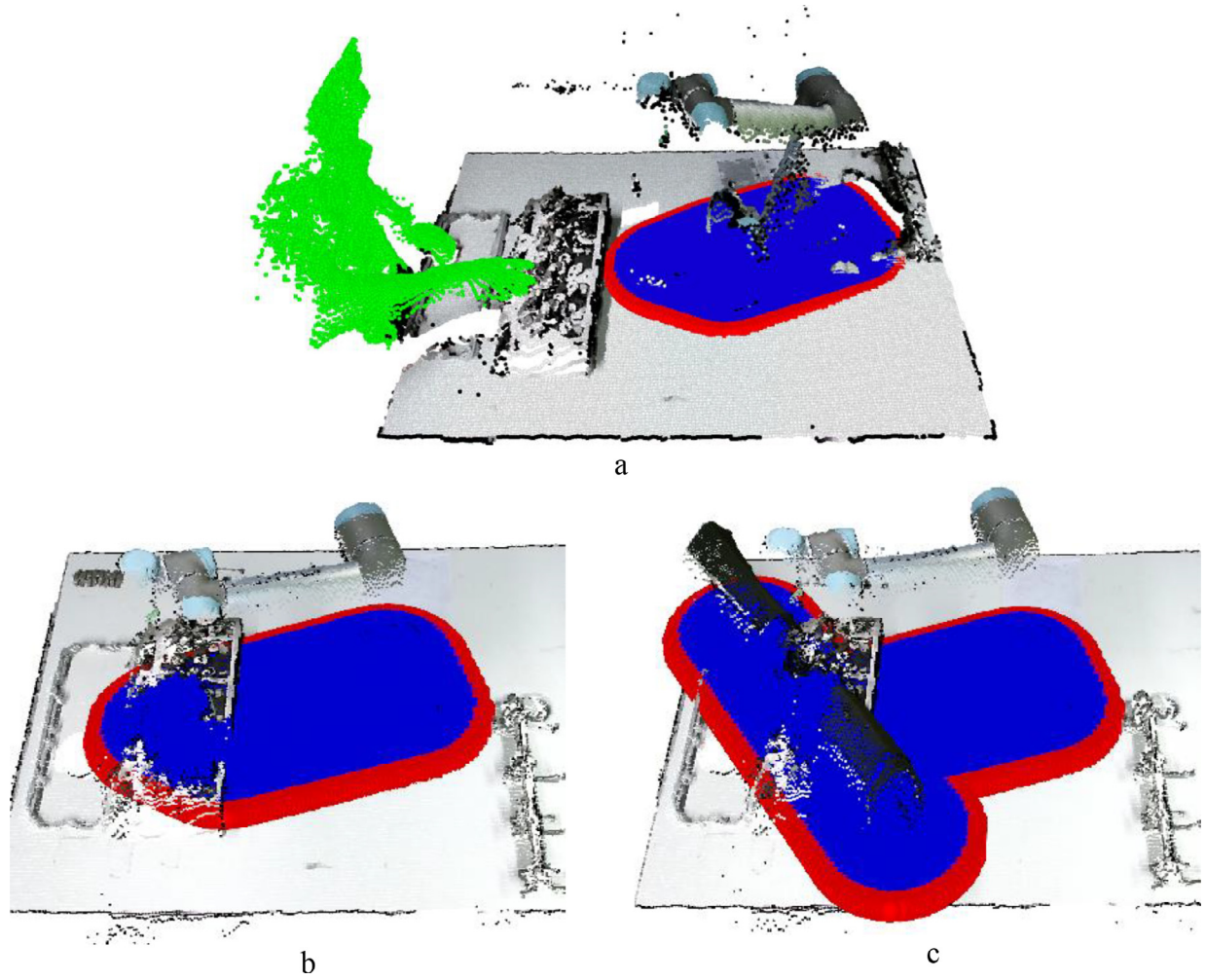


Fig. 2. a) Shared workspace S is modelled as a depth map image where three virtual zones are defined: robot zone (blue), human zone (gray) and danger zone (red); b) robot approaching to grasp an object; c) robot zone extended to cover the carried object.

sensor which can be modelled as a pin-hole camera parametrized by two matrices: the intrinsic camera matrix K , modelling the projection of a Cartesian point to an image plane, and the extrinsic camera matrix $(R|t)$, describing the pose of the camera in the world. The matrices can be solved by the chessboard calibration procedure [46]. For simplicity the model uses the robot coordinate frame as the world frame.

After calibration, the points p in the depth sensor plane can be transformed to a Cartesian point in the world frame and finally to the workspace model $I_s = \{x\}_i$ of the size $W \times H$:

$$P = N^{-1}(RK^{-1}p + t) \quad (1)$$

$$x = T_{proj}P \quad (2)$$

where N^{-1} is the inverse coordinate transformation and T_{proj} is the projective transformation. Now, computations are done efficiently in I_s and (1) is used to display the results to the AR hardware and (2) to map the robot control points (Section 3.2) to the workspace model.

3.2. Binary zone masks

Since all computation is done in the depth image space I_s the three virtual zones can be defined as binary masks of the size $W \times H$: the robot zone Z_r , the danger zone Z_d and the human zone Z_h .

a) *The robot zone mask Z_r :* The zone is initialized using set of control points C_r containing minimum number of 3D points covering all the extreme parts of the robot. The point locations in the robot frame

are calculated online using a modified version of the robot kinematic model and projected to I_s . Finally, the projected points are converted to regions having radius of ω and a convex hull [47] enclosing all the regions is computed and the resulting hull is rendered as a binary mask M_r representing Z_r .

b) *The danger zone mask Z_d :* Contour of the Z_r and constructed by adding a danger margin $\Delta\omega$ to the robot zone mask and then subtracting Z_r from the results:

$$Z_d = M_r(\omega + \Delta\omega) \setminus Z_r \quad (3)$$

c) *The human zone mask Z_h :* This is straightforward to compute as a binary operation since the human zone is all pixels not occupied by the robot zone Z_r or the danger zone Z_d :

$$Z_h = I_s \setminus (Z_r \cup Z_d) \quad (4)$$

3.3. Adding the manipulated object to Z_r and Z_d

An important extension of the model is that the known objects that the robot manipulates are added to the robot zone Z_r and Z_d (see Fig. 2c). This guarantees that the robot does not accidentally hit the operator with an object it is carrying. In such case a new set of control points C_{obj} is created using known dimensions of the object and the robot current configuration. Finally, the binary mask M_{obj} for the object

is created similarly as M_r and the final shape of the zones are computed by fast binary operations:

$$Z_r = M_r(\omega) \cup M_{obj}(\omega) \quad (5)$$

$$Z_d = M_r(\omega + \Delta\omega) \cup M_{obj}(\omega + \Delta\omega) \setminus Z_r \quad (6)$$

3.4. Safety monitoring

The main safety principle is that the depth values in the danger region Z_d must match with the stored depth model. Any change must produce immediate halt of the system. The depth-based model in the robot frame I_s provides now fast computation since the change detection is computed as a fast subtraction operation

$$I_\Delta = \|I_s - I\| \quad (7)$$

where I is the most recent depth data transferred to same space as the workspace model. The difference bins (pixels) are further processed by Euclidean clustering [48] to remove spurious bins due to noisy sensor measurements. Finally, the safety operation depends on which zone a change is detected:

$$\forall x \mid I_\Delta(x) \geq \tau \begin{cases} \text{if } x \in Z_d \text{ (HALT)} \\ \text{if } x \in Z_r \text{ } I_s(x) = I(x) \\ \text{if } x \in Z_h \text{ } M_h = 0, \text{ } M_h(x) = 1 \end{cases} \quad (8)$$

where τ is the depth threshold. In the first case, the change has occurred in the danger zone Z_d and therefore the robot must be immediately halted to avoid collision. For maximum safety this processing stage must be executed first and must test all pixels x before the next stages.

In the second case, the change has occurred in the robot working zone Z_r and is therefore caused by the robot itself by moving and/or manipulating objects and therefore the workspace model I_s can be safely updated. In the last case, the change has occurred in the human safety zone Z_h and therefore the mask M_h is created that represents the changed bins (note that the mask is recreated for every measurement to allow temporal changes, but it does not affect robot operation). Robot can continue operation normally, but if its danger zone intersects with any 1-bin in M_h , then these locations must be verified from the human co-worker via the proposed UIs.

If the bins are verified, then these values are updated to the workspace model I_s and operation continues normally. Note that the system does not verify each bin separately, but a spatially connected region of changed bins. This operation allows a shared workspace and arbitrary changes in the workspace which do occur away from the danger zone.

4. The user interfaces

The danger zone defined in Section 3.2 and various UI components are rendered to graphical objects in two AR setups, shown in Fig. 3.

4.1. UI components

The proposed UI contains the following interaction components (Fig. 3): 1) a danger zone that shows the region operators should avoid; 2) highlighting changed regions in the human zone; 3) *GO* and *STOP* buttons to start and stop the robot; 4) *CONFIRM* button to verify and add changed regions to the current model; 5) *ENABLE* button that needs to be pressed simultaneously with the *GO* and *CONFIRM* buttons to take effect; and 6) a graphical display box (image and text) to show the robot status and instructions to the operator.

The above UI components were implemented to two different hardware, projector-mirror and HoloLens. The UI components and layout were the same for the both hardware to be able to compare the human experience on two different types of hardware.

4.2. Projector-mirror AR

The projector-mirror setup is adopted from [11,49,26] with the main difference that the multiple RGB cameras are replaced with a single RGB-D sensor (Kinect v2). A standard 3LCD projector is installed to the ceiling to point to a 45° tilted mirror that re-projects the picture to the workspace area. The mirror is needed to expand the projection area of the standard projector but could be replaced with a wide-angle lens projector. The projector outputs a 1920 × 1080 color image with 50 Hz frame rate. The projector coordinate frame is calibrated to the world (robot) coordinate frame using the inverse camera calibration with a checkerboard pattern [50].

4.3. Wearable AR (HoloLens)

As a state-of-the-art head-mounted AR display, Microsoft HoloLens is adopted. The headset can operate without any external cables and the 3D reconstruction of the environment as well as accurate 6-DoF localization of the head pose is provided by the system utilizing an internal IMU sensor, four spatial-mapping cameras, and a depth camera. The data exchange between HoloLens and the proposed model is done using wireless TCP/IP. For the work a Linux server was implemented that synchronizes data from the robot simulator (ROS) to HoloLens and back. As HoloLens is not a safety rated equipment at this development phase, the safety and monitoring system is used, but not shown to the user. In Fig. 4 is illustrates the working posture with HoloLens.

The interaction buttons are displayed as semi-transparent spheres that are positioned similar to the projector-mirror UI (Fig. 1). In addition, the safety region is rendered as a solid virtual fence. The fence is rendered as a polygonal mesh having semi-transparent red texture. From the 2D boundary and a fixed fence height the fence mesh is constructed from rectangular quadrilaterals that are further divided to two triangles for the HoloLens rendering software.

The UI component and the virtual fence coordinates P are defined in the robot frame and transformed to the HoloLens frame by

$$P' = (T_{AR}^R T_H^{AR})^{-1} P \quad (9)$$

where T_{AR}^R is a known static transformation between the robot and an AR marker (set manually to the workspace) and T_H^{AR} is the transformation between the marker and the user holographic frame. Once the pose has been initialized the marker can be removed and during run time T_H^{AR} is updated by HoloLens software.

5. Engine assembly task

The task used in the experiments is adopted from a local diesel engine manufacturing company. In addition to the proposed safety model and the interaction interfaces, a baseline method where the human and robot cannot work side-by-side is presented for comparison.

5.1. Task description

The task consists of five sub-tasks (Task 1–5) that are conducted by the operator (blue) or the robot (red) or both (yellow). Task 4 is the collaborative sub-task where a rocker shaft is held by the robot and carefully positioned by the operator.

The task used in the experiments is a part of a real engine assembly task from a local company. The task is particularly interesting as one of the sub-tasks is to insert a rocker shaft that weights 4.3 kg and would therefore benefit from HRC. The task is illustrated in Fig. 5 which also shows the five sub-tasks (H denotes the human operator and R the robot):

- Task 1) Install 8 rocker arms (H),
- Task 2) Install the engine frame (R),
- Task 3) Insert 4 frame screws (H),

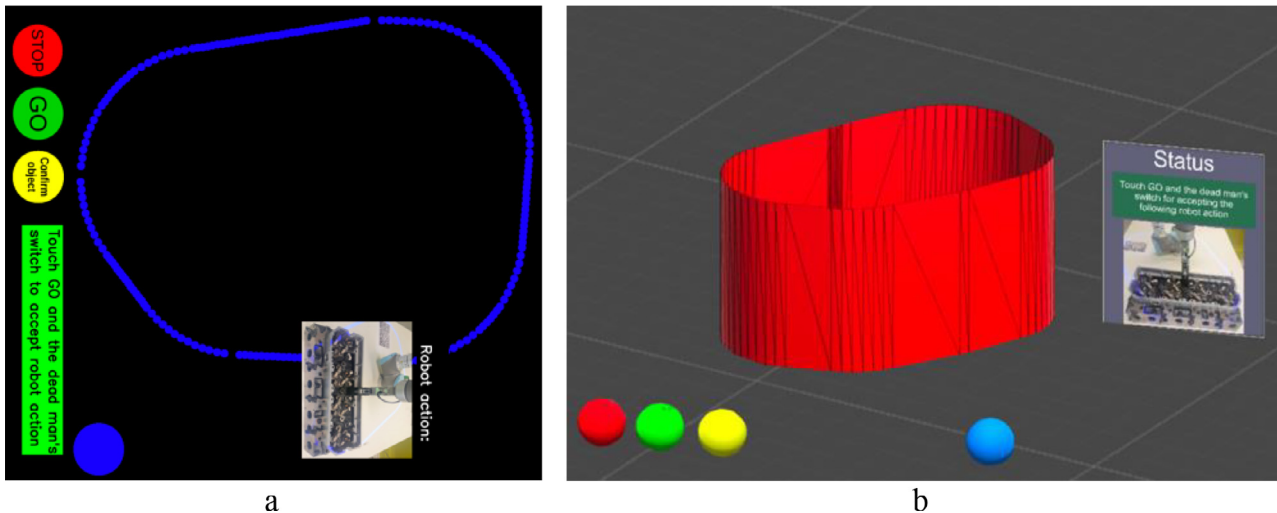


Fig. 3. UI graphics: a) projector-mirror as a 2D color image and b) the HoloLens setup rendered in Unity3D engine.

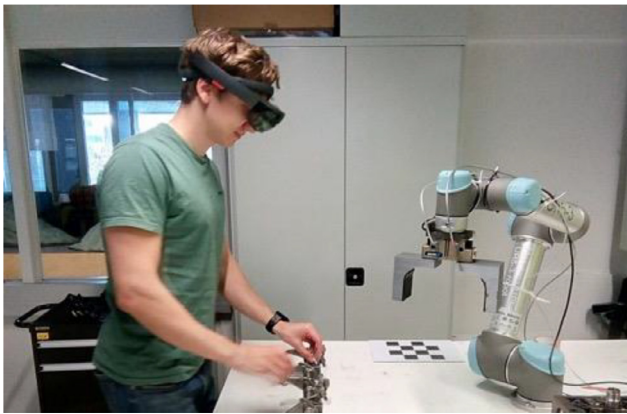


Fig. 4. Test set-up before the experiment with HoloLens.

- Task 4) Install the rocker shaft (R + H) and
- Task 5) Insert the nuts on the shaft (H).

Tasks 1–3 and 5 are dependent so that the previous subtask must be completed before the next can begin. Task 4 is collaborative in the sense that the robot brings the shaft and moves to a force mode allowing physical hand-guidance of the end-effector. In the force mode, the robot applies just enough force to overcome the gravitational force of the object while still allowing the human to guide the robot arm for accurate positioning.

5.2. A non-collaborative baseline

The baseline system is based on the current practices in manufacturing - the human and robot cannot operate in the same workspace simultaneously. In the setting, the operator must stay 4 m apart from the robot when the robot is moving and the operator is allowed to enter the workspace only when the robot is not moving. In this scenario the collaborative Task 4 is completely manual, the robot only brings the part. Safety in the baseline is ensured by an enabling switch button which the operator needs to press all the time for the robot to be operational. The baseline does not contain any UI components, but in the user studies the subjects are provided with textual descriptions for all sub-tasks.

6. Experiments

In this section quantitative and qualitative results are reported for the assembly task and the three different setups are compared.

6.1. Settings

The experiments were conducted using the model 5 Universal Robot Arm (UR5) and OnRobot RG2 gripper. Kinect v2 was used as the depth sensor installed to the ceiling and capturing the whole workspace area. The AR displays, the projector or HoloLens, were connected to a single laptop with Ubuntu 16.04 OS and it performed all computations. In the study, a safe work environment was implemented. The interaction is facilitated with a collaborative robot, reduced speed and force and by the projection of safety zones on the work environment. A risk

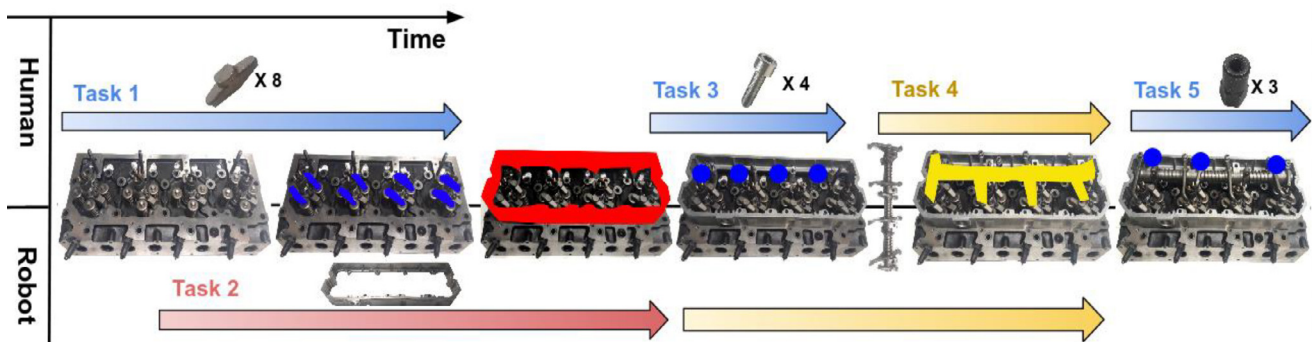


Fig. 5. The engine assembly task used in the experiments.

Table 1
The questionnaire template developed and used in the user experience studies.

Categories	Individual questions
Safety	Q1. The job has a low risk of accident. Q2. The safety system improves the workflow in a safe way.
InformationProcessing	Q3. A lot of time was required to learn the equipment used on the job. Q4. The job requires me to analyze a lot of information.
Ergonomics	Q5. Body posture and movement arrangements on the job are suitable. Q6. The job requires a lot of physical effort. Q7. The job requires a great deal of muscular strength.
Autonomy	Q8. During task, I felt a sense of choice and freedom in the things I undertake.
Competence	Q9. Robot system considers how I would like to do things. Q10.1 feel disappointed with my performance in my task.
Relatedness	Q11. Robot conveyed confidence in my ability to do well in my task. Q12.1 feel my relationship with robot at the task was just superficial. Q13. Robot I work with is friendly.

assessment based on [51] was carried out and residual risks were deemed acceptable.

6.2. User studies

The experiments were conducted with 20 unexperienced volunteered university students. Responsible conduct of research and procedures for handling allegations of misconduct in Finland's instructions by the Finnish Advisory Board on Research Integrity were followed. The ethics Committee of the Tampere region, hosted by University of Tampere, provides ethical guidelines for conducting non-medical research in the field of the human science. These guidelines are outlined as i) Respecting the autonomy of research subjects, ii) Avoiding harm, and iii) Privacy and data protection based on guidelines of The Finnish Advisory Board on Research Integrity. The participation was not mandatory and participants could leave any time they chose.

The data collection included collection of performance times, that were recorded, and after experimenting the three systems they were asked the questionnaire in Table 1. No personal data was collected during the experiment. The goal of the questionnaire was to evaluate physical and mental stress aspects of the human co-workers during the task. The questions were selected to cover safety, ergonomics and mental stress experience as defined in Salvendy et al. [52] and autonomy, competence, and relatedness in Deci et al. [53]. Users were asked to score each question using the scale from 1 (totally disagree) to 5 (totally agree).

6.3. Quantitative performance

For quantitative performance evaluation two different metrics were used, Average total task execution time and Average total robot idle time, that measure the total performance improvement and the time robot is waiting for the operator to complete her tasks, respectively.

The results in Fig. 6 show that the both AR-based interactive systems outperform the baseline where the robot was not moving in the same workspace with an operator. The difference can be explained by the robot idle time which is much less for AR-based interaction. The difference between the HoloLens and projector-based systems is marginal. On average, the AR-based systems were 21–24% and 57–64% faster than the baseline in the terms of the total execution time and the robot idle time respectively.

6.4. Subjective evaluation

Since the results from the previous quantitative evaluation of system performance were similar for the both HoloLens and projector-based AR interaction the user studies provided important information about the differences of the two systems.

All the 20 participants answered to the 13 template questions (Q1-

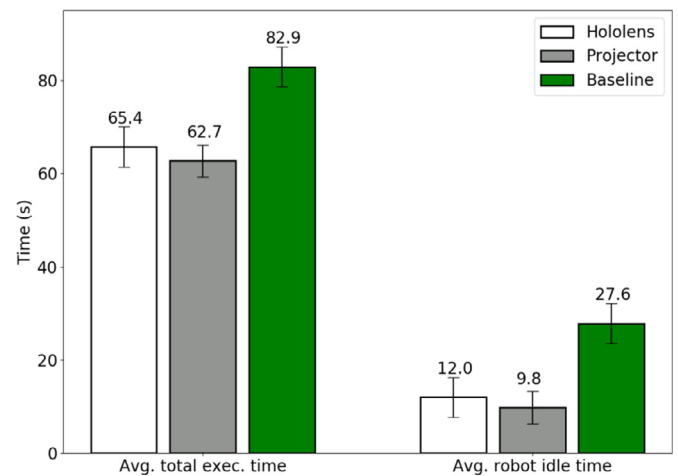


Fig. 6. Average task execution and robot idle times from the user studies.

Q13) listed in Table 1, and the results analyzed. The average scores with the standard deviations are shown in Fig. 7. The overall impression is that the projector-based display outperforms the two others (HoloLens and baseline), but surprisingly HoloLens is found inferior to the baseline in many safety related questions. The numerical values are given in Table 2 and these verify the overall findings. The projector-based method is considered the safest and the HoloLens-based method most unsafe with a clear margin.

Based on the analysis the results and free comments from the user studies, the HoloLens is experienced most unsafe due to the intrusiveness of the device. Even though it is used as augmented display (information virtually added to the scene), it blocks, to some extent, the view of the operator. Additionally, the device is quite heavy, which can create discomfort and decrease the feeling of safety. The projector-based system does not experience these features and, therefore, is experienced most safe. The amount of information needed to understand the task is smallest for the baseline while projector-based has very similar numbers and again the HoloLens-based method was found clearly more difficult to understand.

Ergonomics-wise the HoloLens and projector-based methods were superior likely to the fact that they provided help in installing the heavy rocker shaft. The autonomy numbers are similar for all methods, but the projector-based is found the easiest to work with. The users also found their performance best with the projector-based system (Competence). The question Q12 was obviously difficult to understand for the users, but all users found the system with AR interaction more plausible (Q13) than the baseline without interaction. Overall, the projector-based AR interaction in collaborative manufacturing was found safer and more ergonomic than the baseline without AR interaction and also the HoloLens-based AR.

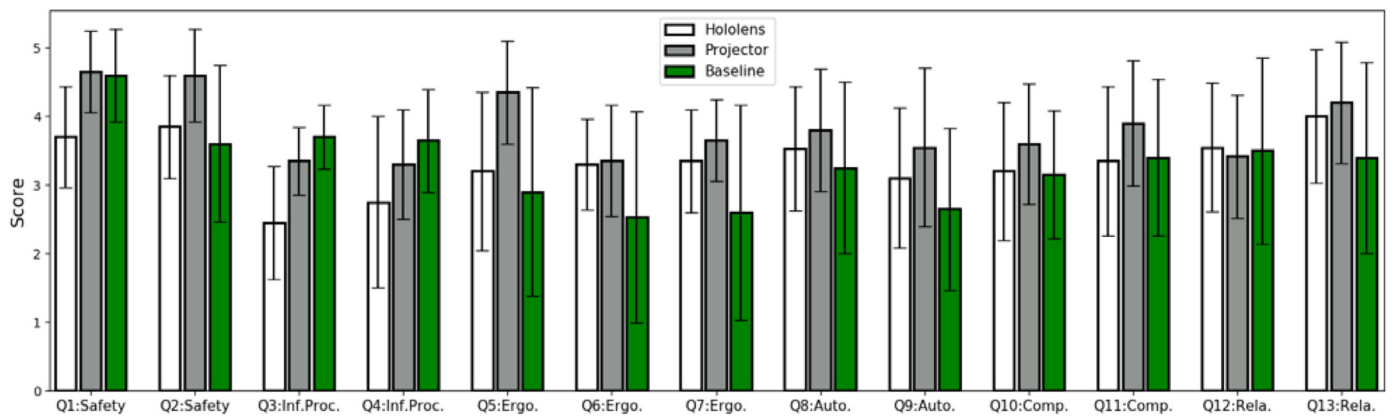


Fig. 7. Average scores for the questions Q1-Q13 used in the user studies (20 participants). Score 5 denotes “totally agree” and 1 “totally disagree” and scores for the questions Q3, Q4, Q6, Q7 and Q10 are inverted for better readability (score 5 has the same meaning as for other questions).

Table 2

Average scores for the question (Q1-Q13). Higher is better except for those marked with “-”. The best result emphasized (multiple if no statistical significance).

		HoloLens	Projector	Baseline
Safety	Q1	3.7	4.7	4.6
	Q2	3.9	4.6	3.6
InformationProcessing!	Q3-	2.6	1.7	1.3
	Q4-	2.3	1.7	1.4
Ergonomics	Q5	3.2	4.4	2.9
	Q6-	1.7	1.7	2.5
	Q7-	1.7	1.4	2.4
Autonomy	Q8	3.5	3.8	3.3
	Q9	3.1	3.6	2.7
Competence	Q10-	1.8	1.4	1.9
	Q11	3.4	3.9	3.4
Relatedness	Q12	3.6	3.4	3.5
	Q13	4.0	4.2	3.4

Below are free comments from the user studies that well point out the reasons why different systems were preferred or considered difficult to use:

- HoloLens:
 - “Too narrow field of view, head has to be rotated a lot.”
 - “Feels heavy and uncomfortable after a while.”
 - “Holograms feels to be closer than they actually are.”
- Projector:
 - “I would choose the projector system over HoloLens”
 - “Easier and more comfortable to use”
- Baseline:
 - “System could be fooled by placing object on the switch button.”

7. Conclusions

This paper described a computation model of the shared workspace in HRC manufacturing. The model allows to monitor changes in the workspace to establish safety features. Moreover, the paper proposed a UI for HRC in industrial manufacturing and implemented it on two different hardware for AR, a projector-mirror and wearable AR gear (HoloLens). The model and UIs were experimentally evaluated on a realistic industrial assembly task and results from quantitative and qualitative evaluations with respect to performance, safety and ergonomics, and against a non-shared workspace baseline were evaluated. In experiments on a realistic assembly task adopted from the automotive sector both AR-based systems were found superior in performance to the baseline without a shared workspace. However, the users found the projector-mirror system clearly more plausible for

manufacturing work than the HoloLens setup. The other AR research papers considering traditionally conveyed AR e.g. via monitors or tablets reported that AR technologies receives positive feedback from the potential users. The studies agree with this indication, except when using wearable AR such as head mounted HoloLens. The wearable AR requires still more technical maturity (in design, safety and software side) in order to be considered suitable for industrial environments. The future work includes experiments in a multimachine work environment, where the human worker operates together with more traditional industrial robots (payload up to 50 kg) and mobile robots. In addition, improvements on the existing interfaces are planned based on the feedback received from the end users, such as projecting the UI components on movable/adjustable table for increased comfort. Lastly, future experiments include the latest generation of Microsoft HMD (HoloLens 2) that has improved on the previous technical, visual, and functional aspects of HoloLens 1.

Declaration of Competing Interest

We promise no conflict of interest exists in the submission of this manuscript, and this manuscript is approved by all authors for publication.

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Supplementary materials

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References

- [1] H. Flegel, Manufature High-Level Group, Manufature Vision 2030: Competitive, Sustainable And, Manufature Implementation Support Group, 2018.
- [2] euRobotics, “Robotics 2020 - strategic research agenda for robotics in Europe,” 2013, p. 101.
- [3] L. Wang, R. Gao, J. Vánca, J. Krüger, X. Wang, S. Makris, G. Chryssolouris, Symbiotic human-robot collaborative assembly, CIRP Ann. 68 (2) (2019) 701–726.
- [4] R.-J. Halme, M. Lanz, J. Kämäräinen, R. Pieters, J. Latokartano, A. Hietanen, Review of vision-based safety systems for human-robot collaboration, Procedia CIRP 72 (2018) 111–116.
- [5] R.-G. Sandra, V.M. Becerra, J.R. Llata, E. Gonzalez-Sarabia, C. Torre-Ferrero, J. Perez-Oria, Working together: a review on safe human-robot collaboration in industrial environments, IEEE Access 5 (2017) 26754–26773.
- [6] ISO/TS 15066:2016 Robots and Robotic, International Organization for Standardization, 2016.
- [7] M. Bdiwi, M. Pfeifer, A. Sterzing, A new strategy for ensuring human safety during

- various levels of interaction with industrial robots, *CIRP Ann.* 66 (2017) 453–456.
- [8] E. Mariotti, E. Magrini, A.D. Luca, Admittance control for human-robot interaction using an industrial robot equipped with a f/t sensor, *International Conference on Robotics and Automation (ICRA)*, 2019.
- [9] P. Tsarouchi, S. Makris, G. Chryssolouris, Human-robot interaction review and challenges on task planning and programming, *Int. J. Comput. Integr. Manuf. (IJCIM)* 29 (2016) 916–931.
- [10] H. Liu, L. Wang, An AR-based worker support system for human-robot collaboration, *Proc. Manuf.* 11 (2017) 22–30.
- [11] C. Vogel, C. Walter, N. Elkmann, Safeguarding and supporting future human-robot cooperative manufacturing processes by a projection-and camera-based technology, *Proc. Manuf.* 11 (2017) 39–46.
- [12] C. Gkourmelos, P. Karagiannis, N. Kousi, G. Michalos, S. Koukas, S. Makris, Application of wearable devices for supporting operators in human-robot cooperative assembly tasks, *Proc. CIRP* 76 (2018) 177–182.
- [13] J. Gea Fernández, D. Mronga, M. Günther, T. Knobloch, M. Wirkus, M. Schröer, M. Trampler, S. Stiene, E. Kirchner, V. Bargsten, Multimodal sensor-based whole-body control for human-robot collaboration in industrial settings, *Rob. Auton. Syst.* 64 (2017) 102–119.
- [14] E. Magrini, F. Ferraguti, A.J. Ronga, F. Pini, A. De Luca, F. Leali, Human-robot coexistence and interaction in open industrial cells, *Rob. Comput.-Integr. Manuf. (RCIM)* 61 (2020) 120–143.
- [15] R.K. Ganesan, Y.K. Rathore, H.M. Ross, H.B. Amor, Better teaming through visual cues: how projecting imagery in a workspace can improve human-robot collaboration, *IEEE Rob. Autom. Mag.* 25 (2018) 59–71.
- [16] Safety Requirements For Industrial robots, ISO 10218-1:2011, International Organization for Standardization, 2011.
- [17] Robots For Industrial environments, ISO 10218-1:2006, International Organization for Standardization, 2006.
- [18] J.A. Marvel, Performance metrics of speed and separation monitoring in shared workspaces, *IEEE Trans. Autom. Sci. Eng.* 10 (2013) 405–414.
- [19] C. Sloth, H.G. Petersen, Computation of safe path velocity for collaborative robots, *International Conference on Intelligent Robots and Systems (IROS)*, 2018.
- [20] G. Michalos, N. Kousi, P. Karagiannis, C. Gkourmelos, K. Dimoulas, S. Koukas, K. Mparis, A. Papavasileiou, S. Makris, Seamless human robot collaborative assembly: an automotive case study, *Mechatronics* 55 (2018) 194–211.
- [21] G. Michalos, S. Makris, P. Tsarouchi, T. Guasch, D. Kontovrakis, G. Chryssolouris, Design considerations for safe human-robot collaborative workplaces, *Proc. CIRP* 37 (2015) 248–253.
- [22] P.A. Lasota, T. Fong, J.A. Shah, A survey of methods for safe human-robot interaction, *Found. Trends Rob.* 5 (2017) 261–349.
- [23] SafetyEYE, Pilz GmbH & Co., 2014.
- [24] S. Kock, J. Bredahl, P.J. Eriksson, M. Myhr, K. Behnisch, Taming the robot better safety without higher fences, *ABB Rev.* (2006) 11–14.
- [25] F. Vicentini, M. Giussani, L.M. Tosatti, Trajectory-dependent safe distances in human-robot interaction, *Emerging Technology and Factory Automation (ETFA)*, 2014.
- [26] C. Vogel, M. Poggendorf, C. Walter, N. Elkmann, Towards safe physical human-robot collaboration: a projection-based safety system, *International Conference on Intelligent Robots and Systems (IROS)*, 2011.
- [27] E. Kim, R. Kirschner, Y. Yamada, S. Okamoto, Estimating probability of human hand intrusion for speed and separation monitoring using interference theory, *Rob. Comput.-Integr. Manuf. (RCIM)* 61 (2020) 80–95.
- [28] C. Byner, B. Matthias, H. Ding, Dynamic speed and separation monitoring for collaborative robot applications—concepts and performance, *Rob. Comput.-Integr. Manuf. (RCIM)* 58 (2019) 239–252.
- [29] J.A. Marvel, R. Norcross, Implementing speed and separation monitoring in collaborative robot workcells, *Rob. Comput.-Integr. Manuf. (RCIM)* 44 (2017) 144–155.
- [30] J.-H. Chen, K.-T. Song, Collision-free motion planning for human-robot collaborative safety under cartesian constraint, *International Conference on Robotics and Automation (ICRA)*, 2018.
- [31] M.P. Polverini, A.M. Zanchettin, P. Rocco, A computationally efficient safety assessment for collaborative robotics applications, *Robot. Comput. Integr. Manuf.* 46 (2017) 25–37.
- [32] F. Flacco, T. Kröger, A. De Luca, O. Khatib, A depth space approach to human-robot collision avoidance, *International Conference on Robotics and Automation (ICRA)*, 2012.
- [33] F. Fabrizio, A. De Luca, Real-time computation of distance to dynamic obstacles with multiple depth sensors, *IEEE Rob. Autom. Lett.* 2 (2016) 56–63.
- [34] M. Cefalo, E. Magrini, G. Oriolo, Parallel collision check for sensor based real-time motion planning, *International Conference on Robotics and Automation (ICRA)*, 2017.
- [35] X. Zhao, J. Pan, Considering human behavior in motion planning for smooth human-robot collaboration in close proximity, *International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 2018.
- [36] H. Rajnathsing, C. Li, A neural network based monitoring system for safety in shared work-space human-robot collaboration, *Industr. Rob.* 45 (2018) 481–491.
- [37] H. Liu, T. Fang, T. Zhou, Y. Wang, L. Wang, Deep learning-based multimodal control interface for human-robot collaboration, *Procedia CIRP* 72 (2018) 3–8.
- [38] P. Wang, H. Liu, L. Wang, R.X. Gao, Deep learning-based human motion recognition for predictive context-aware human-robot collaboration, *CIRP Ann.* 67 (2018) 17–20.
- [39] S.A. Green, M. Billingham, X. Chen, J.G. Chase, Human-robot collaboration: a literature review and augmented reality approach in design, *Int. J. Adv. Rob. Syst. (IJARS)* 5 (2008) 1.
- [40] S. Sato, S. Sakane, A human-robot interface using an interactive hand pointer that projects a mark in the real work space, *International Conference on Robotics and Automation (ICRA)*, 2000.
- [41] R.S. Andersen, O. Madsen, T.B. Moeslund, H.B. Amor, Projecting robot intentions into human environments, *International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 2016.
- [42] R.C. Arkin, T.R. Collins, Skills Impact Study For Tactical Mobile Robot Operational Units, Georgia Institute of Technology, 2002.
- [43] E. Rosen, W. David, P. Elizabeth, C. Gary, T. James, K. George, T. Stefanie, Communicating and controlling robot arm motion intent through mixed-reality head-mounted displays, *Int. J. Rob. Res.* 38 (2019) 1513–1526.
- [44] D.Q. Huy, I. Vietcheslav, G.S.G. Lee, See-through and spatial augmented reality—a novel framework for human-robot interaction, *International Conference on Control, Automation and Robotics (ICCAR)*, 2017.
- [45] J. Elsdon, Y. Demiris, Augmented reality for feedback in a shared control spraying task, *International Conference on Robotics and Automation (ICRA)*, 2018.
- [46] B. M., F.C. Park, Robot sensor calibration: solving $AX = XB$ on the Euclidean group, *Trans. Rob. Autom.* (1994).
- [47] F. Y., R.L. Graham, Finding the convex hull of a simple polygon, *J. Algo.* 4 (4) (1983) 324–331.
- [48] R.B. Rusu, Semantic 3d object maps for everyday manipulation in human living environments, *Künstliche Intelligenz* 24 (4) (2010) 345–348.
- [49] C. Vogel, C. Walter, N. Elkmann, A projection-based sensor system for safe physical human-robot collaboration, *International Conference on Intelligent Robots and Systems (IROS)*, 2013.
- [50] M. Ivan, K. Joni-Kristian, L. Lasse, Projector calibration by inverse camera calibration, *Scandinavian Conference on Image Analysis (SCIA)*, 2011.
- [51] Safety of Machinery, ISO 12100:2010, International Organization for Standardization, 2015.
- [52] G. Salvendy, *Handbook of Human Factors and Ergonomics*, John Wiley & Sons, 2012.
- [53] E.L. Deci, R.J. Vallerand, L.G. Pelletier, R.M. Ryan, Motivation and education: the self-determination perspective, *Educ. Psychol.* 26 (3–4) (1991) 325–346.