

Proof of concept of a projection-based safety system for human-robot collaborative engine assembly

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Abstract—In the past years human-robot collaboration has gained interest among industry and production environments. While there is interest towards the topic, there is a lack of industrially relevant cases utilizing novel methods and technologies. The feasibility of the implementation, worker safety and production efficiency are the key questions in the field. The aim of the proposed work is to provide a conceptual safety system for context-dependent, multi-modal communication in human-robot collaborative assembly, which will contribute to safety and efficiency of the collaboration. The approach we propose offers an addition to traditional interfaces like push buttons installed at fixed locations. We demonstrate an approach and corresponding technical implementation of the system with projected safety zones based on the dynamically updated depth map and a graphical user interface (GUI). The proposed interaction is a simplified two-way communication between human and the robot to allow both parties to notify each other, and for the human to coordinate the operations.

I. INTRODUCTION

Within all areas of robotics, the demand for collaborative and more flexible robot systems is expected to rise [1], [2]. In the automation industry, for example, industrial and collaborative robotics are acting as a driver for market growth. The past decade has therefore seen a growing interest in this technology, for an economic relevance of bringing humans and robots closer together in the manufacturing working environment [3], [4]. The continued rise of industrial robots certainly seems to be inevitable, being driven by a variety of production demands, including the need for safer and more simplified robotic technologies to work in collaboration with humans, increased resource efficiency, and continued adaptation to the proliferation of automation and the Internet of Things (IoT) [5].

In recent years, research on human-robot interaction (HRI) and human-robot collaboration (HRC) has also increased [6], [7]. Manufacturing companies have gradually increased the implementation of collaborative robots assisted by machine vision into their daily production [8], [9]. Flexibility and changeability of assembly processes must be increased, therefore, more advanced interaction and/or collaboration between the operator and the assembly system is required (see Fig. 1). Such interaction is expected to improve complex assembly processes by increasing flexibility of the total system [10]. Particularly in physical interaction, where a worker guides a robot or the robot provides power assistance to the worker, the expectations are high. Furthermore, as concluded

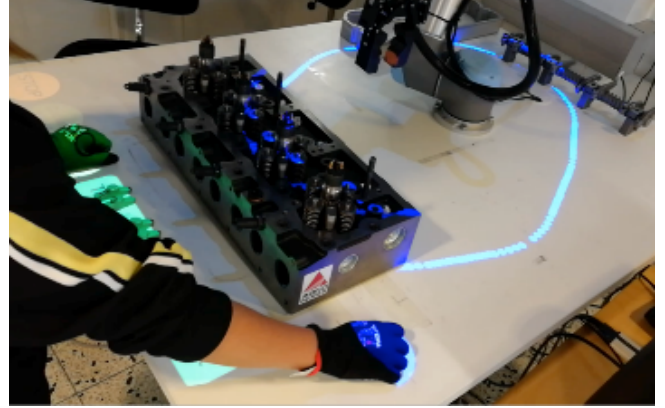


Fig. 1. Collaborative human-robot assembly with projection-based safety system.

in [11] and by our own work [4] it is expected that in the future semi-automated robotized assembly requires industrial robots to collaborate with human workers as part of a team to complete tasks based on their individual competences.

One way to improve the effectiveness of human-robot collaboration is supporting human workers with current task- and context-dependent work instructions via suitable communication modalities. This implies that information presented to an operator should only be relevant to the current task and not to future tasks. Similarly, presented information should be in useful form by utilizing appropriate modalities [12]. For example, a safety zone should be projected around and on top of a shared work space, such that it is most visible for the operator. This approach aims to raise the human understanding of the task in the context of safe human-robot collaboration. The other way around, workers should be supported in controlling the robot or other components of the production system by using suitable modalities as well. Traditional interfaces, such as push buttons, might be less suitable to halt robot motion than, for example, the crossing of virtual and projected light barriers [13], [14]. The developments proposed in this work address these particular issues (see Fig. 1).

In detail, this paper introduces a safety system for context-dependent, multi-modal communication in a collaborative assembly task and presents its implementation towards a real industrial mid-heavy (< 5 kg) assembly task. These developments are an extension of our previous developments [15], which described a prototype of the vision- and projector-based safety system. In particular, the contributions of this

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work are therefore:

- 1) Development of a user interface and interaction to enable suitable task and context-dependent safety communication between human and robot (i.e. projection of current safety zone, virtual buttons).
- 2) Development of a safety-zone monitoring system that reacts when the safety zone is violated.
- 3) Implementation of a case study based on a real industrial assembly task.
- 4) Implementation of a task sequencing and work allocation schedule between human and robot resources for the industrial assembly task.

This paper is organized as follows. Section II provides the theoretical background on the topics of human-machine interaction and human-robot collaboration. Section III proposes the technical developments of the safety system. Section IV presents the industrial case study. Finally, Section V reports conclusions and future works.

II. THEORETICAL BACKGROUND

A. Human Machine Interaction

Human-machine interfaces allow interaction between humans and machines. For reasons of safety and ergonomics, it is crucial that the design of such interaction is smooth, productive and has taken into account the persons comfort and well being. Human-factors which must be considered when designing interaction can be categorized in either physical ergonomics or mental ergonomics (Machine directives regarding ergonomics; Directive 2006/42/EC, Annex I, 1.1.6 "Ergonomics", EN 614 (parts 1-2) Safety of machinery - Ergonomic design principles, CEN, Brussels).

Standards (EN 13861) must be followed which state that the machinery should be designed in the context and consistent with human capabilities, limitations and needs. Therefore, analysis has to be carried out that assesses the effect of the interaction design on the persons safety, health and well-being. Safety must be ensured by considering these characteristics with respect to dangerous areas in a machine. If necessary, extra safety systems have to be installed that halt the machine when a certain barrier is crossed (e.g. light barrier, fence).

Health and well being for physical ergonomics is related to repetitive and awkward body movements or heavy loads. Ergonomics principles for mental workload relate to a person's cognitive abilities and its immediate effects due to the interactive scenario (ISO 10075 series (parts 1-3), Ergonomic principles related to mental workload). Safety aspects due to reduced cognitive abilities may result to long-term health effects and a higher risk of accidents. Cognitive abilities such as attention, memory, reasoning and perception can therefore have a large effect on the safety of interaction. The design of information exchange for interaction is, however, not as simple as reducing mental workload. Mental fatigue, experienced by either too much (repetitive) information or too little (monotonous) information, can have equal effects. Additionally, allocation of tasks between machines and

robots is quite challenging and depends largely on the task and the human factors involved in the collaborative setup [16], [17].

B. Human-Robot Collaboration

Safety for humans in collaboration actions can be ensured by different strategies and methods. The ISO 10218-1/ 2 (2011) standards give safety requirements for robots and robot systems in industrial context, where collaborative operation between a person and a robot sharing a common work space is taken into account. Technical specification (TS) 15066 (2016) provides additional guidance for safe HRI. The standards define four collaborative safeguarding modes:

- 1) Safety-rated monitored stop: The robot cannot enter the collaborative workspace when a human is present in the workspace. When the the robot is present in the workspace and the human enters, the safety-rated monitored stop is activated.
- 2) Hand guiding: Hand-guided motion of the robot is allowed, when a human is guiding the robot with a hand-guiding tool. Again, when a person enters the workspace in which a robot is present, the safety-rated monitored stop is activated.
- 3) Speed and separation monitoring: Safety is guaranteed by ensuring a minimum separation distance between a human and the robot. The separation distance depends on the speed of the robot i.e. lower robot speed allows a smaller separation distance. When the separation distance goes below the protective separation distance, the robot is halted.
- 4) Power and force limiting: Physical contact between a human and the robot is allowed. Risk reduction is done by keeping robot-related hazards below certain limits that are defined in the risk assessment.

There exist numerous studies regarding safety in human-robot interaction and collaboration that adhere to, and even surpass, the standard safeguarding modes. The most relevant works related to our approach are described as follows: Matthias [3] proposed a safety concept with seven levels. Relevant risks can be assessed and reduced to harmless levels by applying suitable measures. The risk/impact evaluation was divided into six levels and give a solid background for system design and risk management. Marvel [18] proposed a set of metrics to evaluate speed and separation monitoring efficiency in shared, industrial work spaces. More recently, Marvel and Norcross [19] proposed an approach for implementing speed and separation monitoring in collaborative robot work cells. Lasota [7] divided safe human-robot interaction into four methods: safety through control, safety through motion planning, safety through prediction and safety through consideration of psychological factors. Pre- and post-collision control methods are included in safety through control. In pre-collision, safety is ensured by using methods such as safety regions, tracking separation distance, and guiding robot motion away from humans. In post-collision, approaches intend to minimize injuries after the

detection of a collision. The aim of safety through motion planning is to compute robot paths and motions that avoid collisions. Lasota [7] pointed out that psychological safety should be taken into consideration by adjusting robot behavior specifically towards the human comfort of interaction.

Additionally, there exist several different types of vision-based safety, monitoring and guidance systems in the field of robotics, however, these are mostly in research state and not commercially available. Halme et al. [4] made an extensive literature review covering recent developments from the field. One notable exception is the Pilz Safety EYE that is available for commercial use [20]. Particularly, Vogel et al. [21] developed a safety monitoring system that uses one or multiple cameras and user interaction provided by a projector. The coexistence of a human and a robot considers hybrid cells classified into the shared tasks and workspace. In such case, the tasks and workspaces of the human and the robot are sequential and are shared accordingly. The design of the HRC cell currently asks for considerable time as there are no ready-made guidelines for such design [22], [23], [24].

III. SHARED WORKSPACE MODEL

The aim of this work is to provide a conceptual safety system for context-dependent, multi-modal communication in human-robot collaborative assembly. To achieve this, a real industrial, manual assembly task was taken and redefined towards a human-robot collaborative assembly task. The computer vision- and projection-based safety system monitors the workspace and enables communication and interaction for the shared assembly task. The depth map of the workspace is continuously updated, and this information is used to ensure the safety of the human.

A. Depth-based workspace model

The workspace S is modelled as a single $W \times H$ depth map image I_S and it represents the geometric structure of the workspace. The model can be updated during run time automatically by the robot itself or by a human co-worker using the proposed user interface described in Section IV-C. The workspace model and the virtual robot zones (Sec. III-B) are aligned with the real robot using a calibrated geometric transformation between the depth sensor and the robot. The workspace is in 3D space (a point cloud), however, since occluded regions could not be monitored with a single depth sensor and due to computational complexity, we found the 2D representation more suitable. A 2D map representation of the workspace allows for fast operations (collision detection, map updating) during run-time compared to other representations such as point clouds or voxel grids.

B. Robot zone concept

On the shared workspace model (collaborative workspace) three spatial zones are generated: robot zone Z_r , danger zone Z_d and human zone Z_h , which are illustrated in Fig. 2. The zones Z_r and Z_h represent spaces where the robot and the human can operate freely, respectively. The robot zone Z_r is initialized using set of control points C_r containing minimum

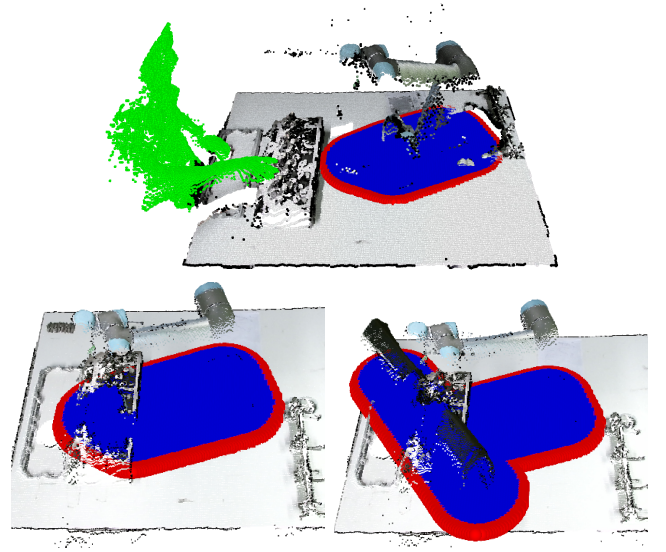


Fig. 2. A shared workspace S is modelled as a depth map image I_S aligned with the robot coordinate system. The robot zone Z_r (blue) is dynamically updated and subtracted from I_S to generate the human zone Z_h (gray). The two zones are separated by the danger zone Z_d (red) which is monitored for safety violations. Changes in Z_h are recorded to binary masks R_i (green). Manipulated objects are enclosed by Z_d and automatically added to Z_r (bottom right).

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 Hawkinses model [25] and projected to I_S . Finally, the projected points are converted to regions having radius of ω and a convex hull [26] enclosing all the regions is computed and the resulting hull is rendered as a binary mask M_r representing Z_r .

The human and robot zone are separated by the danger zone Z_d , where any change causes immediate halt of the robot. The danger zone is constructed by adding a danger zone margin $\Delta\omega$ and then subtracting Z_r from the results:

$$Z_d = M_r(\omega + \Delta\omega) \setminus Z_r. \quad (1)$$

Conceptually, the 2D danger zone Z_d is related to the protective separation distance concept used in the technical standards, which captures a scalar distance value.

The human zone mask Z_h is easy to compute as a binary operation since the human zone is all pixels not occupied by the robot or danger zone:

$$Z_h = I_S \setminus (Z_r \cup Z_d). \quad (2)$$

Workspace changes are detected by monitoring the difference between the current depth data I from the depth sensor and the current workspace model I_S :

$$I\Delta = \|I_S - I\| \quad (3)$$

Substantial changes on $I\Delta$ are detected using a threshold value τ and the operation on the detected bins depends on which zone they lie in:

$$\forall \mathbf{x} \mid I_{\Delta}(\mathbf{x}) \geq \tau \begin{cases} \text{if } \mathbf{x} \in Z_d & \text{HALT} \\ \text{if } \mathbf{x} \in Z_r & I_S(\mathbf{x}) = I(\mathbf{x}) \\ \text{if } \mathbf{x} \in Z_h & M_h = 0, M_h(\mathbf{x}) = 1 \end{cases}, \quad (4)$$

where M_h is a 2D binary mask containing clustered anomalies R_i . During the run time the algorithm must first iterate over all the pixels from the I_{Δ} image and check if any of them fall inside the danger zone Z_d before doing any further processing. If a pixel is detected inside the Z_d the robot is immediately halted and the robot must be manually reset to continue. After the first condition check all the pixels are evaluated against the robot working zone Z_r . If a change has occurred inside Z_r then the workspace model I_S is automatically updated. The main purpose of the zone is to register the movements and/or object manipulations of the robot itself and safely updated them to the model.

Finally, if the pixel has passed all the other checks, the change has occurred in the human safety zone Z_h and we create the mask M_h to represent the changed bins. Note that the mask is re-created for every measurement to allow for temporal changes, however, this does not affect robot operation. The robot continues operation normally, but if its danger zone intersects with any changed bin in M_h , the robot is halted. The changed bins must be verified manually by the human co-worker via our graphical user interface rendered by a projector. If the bins are verified, then these values are updated to the workspace model I_S and operation continues normally. The robot and the human co-worker are isolated to their own operational spaces Z_r and Z_h , respectively, using the danger zone Z_d which spatial margin size is configurable and depends on the system computing - "reaction" -speed. The size of the margin was selected so that the robot had enough time to stop before any parts of the new obstacle could enter inside Z_r . In this work, the margin was heuristically, set to 50 mm. The workspace and safety model is explained in details in [15], where a benchmark experiment is used to demonstrate its capabilities.

C. Ensuring safety during object manipulation

During a collaborative task the robot can carry sharp or heavy object (up to 5kg with UR5) which can potentially harm the human co-worker. In this work we propose an important extension to our previous work [15] by extending the robot zone when the robot is carrying task related objects which exceed the default robot zone. In this scenario we use the known geometric properties of the task related object and the robots grasp point to add new control points to the kinematic model of the robot online. 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:

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

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

In this work ω and $\Delta\omega$ are fixed but can be easily updated during run-time for instance based on the extended protective distance definition (ISO TS 15066).

IV. INDUSTRIAL CASE STUDY

The research and developments are motivated by a real industrial assembly case taken from a local diesel engine manufacturing company (see Fig. 5). The task is the sub-assembly of mid-heavy parts (< 5 kg) to an engine block, as this allowed collaborative robots to be considered. Such collaborative robots have suitable workspace, object handling properties (payload), and offer programmable interaction (hand-guiding). Currently, the studied case is executed via manual assembly, which resulted in a bottleneck in the manufacturing line. Considering a collaborative robot in assembly has the benefit of parallel assembly and the utilization of both the robots and operators expertise (e.g. robot strength, human compliance to tasks), while not introducing the complexities of complete automation. The study considers the feasibility of the implementation with projector and computer vision-based safety system and user experience in the task. Detailed description of the evaluation and results from quantitative and qualitative evaluations with respect to performance, safety and ergonomics are presented in the follow-up paper [27]. Details of the case study, its setup and user interaction are described as follows.

A. Case study description

To evaluate our proposed safety system the manual assembly task was redefined where a human and a robot can work safely in a collaborative manner (see Fig. 3). The safety through consideration of psychological factors [7] was considered in such manner that robot movements were slow, stopping distances at comfortable level, and approach angles were in the field of view of the user. The task consists of a tractor diesel engine sub-assembly that, in the current assembly line, is handled manually. The sub-assembly tasks we consider are the installation of the eight rocker arms, the motor frame, the rocker shaft and finally inserting and tightening the bolts to secure the parts (see Fig. 5). The choice of which steps should be handled by the robot, the operator or as a collaborative assembly depends on many factors, such as object properties (e.g. weight, size, grasp capabilities), assembly complexity (accuracy, speed, robustness) and capabilities of both operator and robot. In this case, the robot handled the heavy parts (frame and rocker shaft) and the operator handled the lighter parts and the assembly (rocker arms, nuts and bolts). The tasks that robot and human are doing, are both parallel and sequential depending on the part they handle (Fig. 4).

Placing the rocker arms and the operations related to bolts and nuts are done individually by the human worker whereas the fetching and positioning of motor frame is done by the robot, further illustrated in Fig. 3. Placing the rocker shaft onto the motor is a delicate task and requires precise positioning, thus this step is done using physical hand-guidance. At first, the robot fetches the rocker shaft

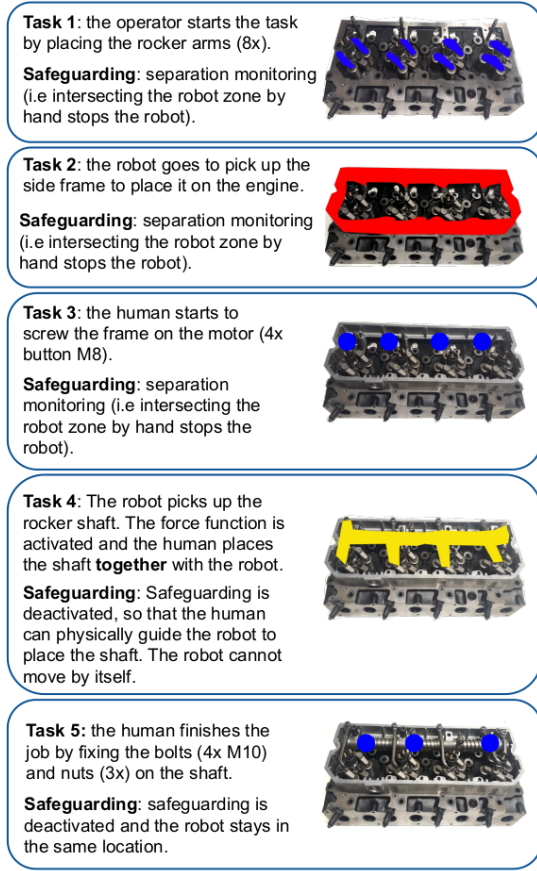


Fig. 3. Description of the assembly steps and resource allocation between human and the robot. The five tasks are conducted by the operator (blue) or the robot (red) or both (yellow)

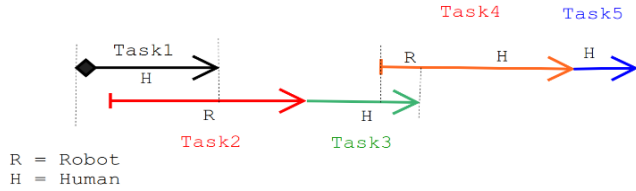


Fig. 4. Task sequencing and work allocation between the resources

and brings it above the engine. After the shaft has arrived and the robot has completely stopped, the safety system is deactivated and the robot is automatically set to a force mode where external forces can be used to move the robot tool center point (TCP) location. The mode requires axis specific forces to be defined which the robot is to apply to its environment. The amount of force to apply is dependent on the weight of the object the robot is carrying and the muscular strength of the human worker. For instance setting the forces too small the TCP will start to drift gradually along the incorrectly set force axis. However, setting the forces too large, the human worker might not have enough strength to drag or pull the TCP along different axes. In the experiments, for all the participants the forces were set to -30N , 10N and 60N along x, y and z-axis respectively.

The physical ergonomics of the assembly task were con-

sidered by having the heavy objects being lifted and guided by the robot. Hand-guiding of the robot with a grasped object is physically ergonomic to the person due to the compensation of the weight of the object and the compliant motion of the robot. Additionally, no buttons need to be pressed to proceed in the sequence of the assembly task. Interaction for potential object or safety zone violations is done via virtual buttons that are projected on the surface of the work environment. Mental stress reduction is considered via appropriate configuration of robot behavior (robot stops when the operator crosses the safety zone) and via the communication of safety zones (projection of safety zone on the table). A video recording of a complete experiment can be found here: <https://youtu.be/v-hM4Nycua4>.

B. Setup and Configuration

Our benchmark system is depicted in Fig. 6. This includes the workspace, hardware components and the main software interfaces. At the top of the workspace a depth sensor (Kinect V2) monitors the area and sends information about the state of the workspace for the robot and the projector. A projector (Epson EB-905) is used to display UI components and robot safety boundaries. The workspace is captured by the depth sensor which is installed at the ceiling perpendicular to the workspace and overseeing both the robot and a human co-worker. The depth sensor works at 30 Hz and provides 512×424 size depth map giving a spatial depth resolution of approximately $5.4 \text{ mm} \times 5.4 \text{ mm}$ on the table surface (2 meters from camera). Due to noisy sensor measurement the resolution was reduced to $10 \text{ mm} \times 10 \text{ mm}$. The IAI Kinect2 library [28] was used to capture, process and deliver depth images to ROS.

A standard 3LCD projector was installed to the ceiling and used to display the user interface and operational information. The projector outputs a 1920×1080 color projection image with 50 Hz frame rate. The physical projection area is increased by installing a mirror in 45° angle to re-project the image to the workspace. The depth sensor and the projector were aligned with the robot's base frame using a standard chessboard calibration method. The ROS interface for the UR5 drivers (communication between high and low-level robot controllers) was taken from the UR modern driver ROS package [29].

C. User interface and interaction

The robot safety zone and UI components were reflected on the planar surface via the projector, and user interaction with the UI was enabled by detecting a change in depth of each individual UI component. The created user interface is shown in Fig. 5.

The START and STOP buttons were the main UI components of the interface model that enable robot operation or stop it immediately, respectively. During initial testing of the system it was noted that the participants could easily start the robot accidentally by bending over the GO button, thus an ENABLE button (colored in blue) was added to the other side of the UI space which needs to be pressed

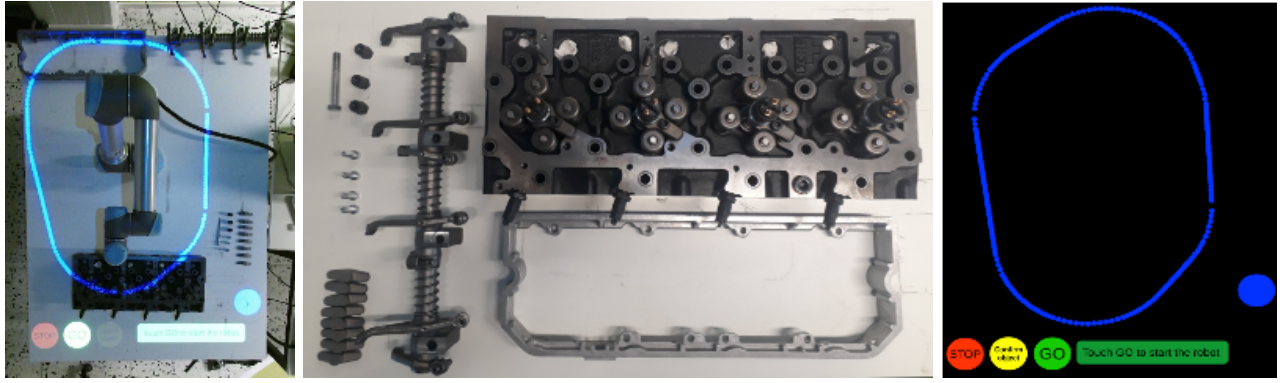


Fig. 5. Left: Top view of the projected work area with the robot and the engine block, surrounded by the assembly parts. Middle: engine block (right top), surrounded by the engine frame (bottom right), rocker shaft (left), rocker arms (bottom left), nuts and bolts. Right: user interface illustrated with buttons, an info bar and a current form of the safety zone.

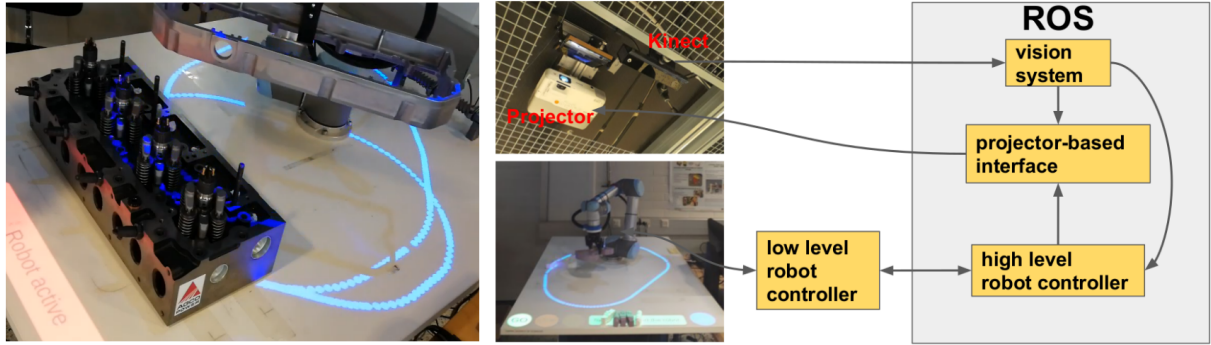


Fig. 6. Overview of the system used in the experiment. Video of a complete experiment: <https://youtu.be/v-hM4Nycua4>

simultaneously with the START button. To manually update the workspace model representation described in Section III another CONFIRM button was added to allow the human operator to confirm unverified regions from the workspace that can be safely added to the workspace model. CONFIRM also requires simultaneous activation of the ENABLE button. In addition to the interaction UI buttons, robot intentions as well as instructions related to the task are displayed for the human operator using an INFORMATION BAR component.

D. Technical limitations

During the experiments it was noted that the average delay between a pause command send by the high-level robot controller until the robot had completely stopped was measured 100 ms. In addition, the projector had another latency of 58 ms in rendering, but this could be avoided with a better projector. Due to the latencies we limited the robot maximum speed to 50% of the maximum to achieve the safe stopping distance (determined heuristically). The average inference time of the algorithm described in Section III with 250×250 size workspace depth map I_S over all user studies was 30 ms. The main computational bottleneck of our method is the heavy preprocessing of the input depth map, which is required due to the noise measurements of the Kinect sensor. Specifically, objects having very reflective or dark surfaces as well as the areas close to depth discontinuities

are problematic and result in corrupted depth estimates and missing information as shown in the point cloud in Fig. 7.

The update and detection rules in Eq. 4 are sensitive to noise and to suppress the effect of these noise pixels we adopt the Euclidean clustering proposed by [30]. The method decomposes the 3D points x , y and Δz of ΔI into clusters based on their Euclidean distance and filters out small sparse clusters. This step is essential for robustness of our method but requires extra computation that depends on the number of points in the ΔI image. However, this process step can be made faster by just down-sampling the depth map. In the experiments the algorithm was configured to filter out clusters having less than 200 points which corresponded roughly an object having 1 cm radius in real world on our setup. The current interaction and visualization components assume a known static surface (flat table). In a dynamic workspace where robot intentions and interaction components have to be precisely projected a more robust tracking-and-projection system has to be implemented [29].

V. CONCLUSIONS

In this paper we proposed a method to support the two-way interaction with a robot by using a vision and a projection-based modality. The approach is described from a technical and user's perspective and can offer a seamless, human-centered and safe collaboration in mid-heavy (< 5 kg) assembly operations. The approach for realizing the GUI

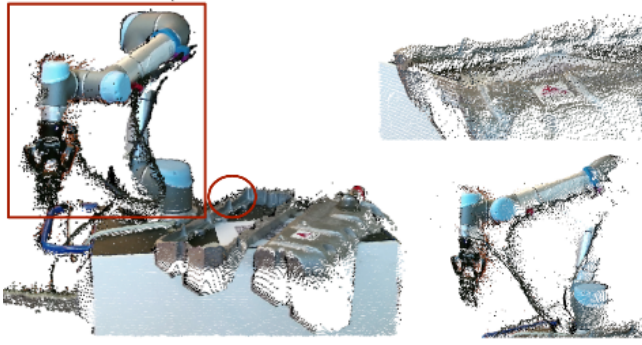


Fig. 7. Sparse outliers (flying pixels) are visible near object boundaries and dark surfaces (below right) and object deformed due to reflective material.

offers an alternative to traditional interfaces like push buttons installed at fixed locations. Experiments were conducted in a laboratory setting with an industrial product (diesel engine assembly). A preliminary user experience assessment indicated that the projector based visual guidance system and GUI, as well as the developed safety system were either considered user friendly, comfortable and safe. The user experience is formally assessed in the follow-up work [27]. The future work includes experiments with more traditional industrial robots, which are not designed as inherently safe. Future work will also further develop and test this approach in a real industrial environment.

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