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Technical paper

XR-based training for technical skills in manufacturing

Henrik Söderlund [a,*], Dan Li [b], Omkar Salunkhe [a], Puranjay Mugur [b], Björn Johansson [a]

[a] *Chalmers University of Technology, Chalmersgatan 4, Gothenburg 412 96, Sweden*
[b] *Volvo Car Corporation, Gunnar Engellaus Väg 8, Gothenburg 418 78, Sweden*

A R T I C L E I N F O

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A B S T R A C T

Manufacturing systems are undergoing rapid transformation driven by global, economic, and sustainability pressures, increasing the need for scalable training solutions to support technical skill development and faster industrialization. However, conventional training methods for manual operations often rely on material-intensive trial-and-error, resulting in material waste, long onboarding times, and dependence on expert supervision. While Extended Reality (XR) has shown strong potential for cognitive and procedural training, its effectiveness for technical, motor-skill–based tasks remain debated due to limited physical interaction, haptic realism, and support for precise tool handling. This study addresses this gap by investigating the use of Mixed Reality (MR) for early-stage technical skill training in manual sealant application within an automotive manufacturing context. An MR training system was developed, integrating physical tools and props to preserve eye-to-hand coordination and interaction fidelity. A lab experiment evaluating tool-tracking accuracy against robotic ground truth data showed an average deviation of 7.7 mm, indicating sufficient precision for early-stage technical skill development when compared to domain specific thresholds. Furthermore, an on-site user study with 45 professional sealant operators assessed usability and acceptance. The results demonstrate high usability and strong user acceptance, with operators reporting increased confidence and reduced reliance on traditional training materials. Additionally, the MR system enabled faster training iterations while reducing material waste and setup time. These findings suggest that XR-based training can effectively support early-stage technical skill development. While evaluated in an automotive sealant application, the approach shows potential for broader applicability to manufacturing tasks requiring tool handling and motor-skills.

1. Introduction

The manufacturing industry is subjected to rapid transitions driven by global and economic pressure that reshapes the demand for production. Shifting geopolitics are redefining where and what we can manufacture, disrupting established supply chains and industrial ecosystems [1]. At the same time, the climate crisis and the push toward net-zero emissions are accelerating changes in what is produced and how it is produced [2]. These external forces are driving a shift in manufacturing processes, workspaces, and job profiles, creating an urgent need for workers with new and adaptable skills [1]. Meanwhile, a paradigm shift towards more human-centric manufacturing, as part of Industry 5.0, is seen, emphasizing the role of human operators empowered by technology [1,3]. Thus, the interest in more scalable and flexible training approaches utilizing technology, such as Extended Reality (XR) training, continues to grow [4]. By creating immersive virtual representations of industrial processes and systems, XR technologies could support interaction between human operators and cyber-physical manufacturing systems to facilitate learning [3].

XR is an umbrella term often used to describe various devices and technologies that can act as an interface between the physical and virtual world, typically through head-mounted displays (HMDs). These technologies differ in the level of immersion and integration they provide and are commonly described along the virtuality continuum as proposed by Milgram and Kishino [5], see Fig. 1.

At one end of this spectrum, Virtual Reality (VR) fully immerses users in a digital environment, removing all direct perception of the physical world [6]. In contrast, Augmented Reality (AR) and Mixed Reality (MR) allow users to remain aware of their real surroundings while overlaying digital content onto the physical environment. These technologies rely on transparent displays or camera-based systems to blend real and virtual elements to various degrees [6]. This means that XR technology has the potential to replace physical artifacts with various degrees of virtual elements used in the training to offer safe, repeatable, and cost-effective

* Corresponding author.
E-mail address: hensode@chalmers.se (H. Söderlund).

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training environments, which makes it highly attractive for the manufacturing industry [7,8].

In the context of training and building technical skills for manufacturing, Dar-El et al., [9] show that two main elements of knowledge are needed and built over time. One, cognitive element, that includes the understanding of "*What to do*", with a large presence during the early phase of the training, focusing on memorizing instructions and information. And one, motor element, tied to the physical skill of knowing "*How to do it*", with a larger presence in the later phases of the training, often achieved through high degree of repetitions in an accurate perceived environment to create muscle memory of movement patterns and execution [10].

Recent reviews show that most of the XR training applications in manufacturing target the first element of technical skills, i.e. cognition through task familiarization and memorization, while only a small part (5%) target the second element, i.e. motor-skills development through repetition [11].

Furthermore, XR, and in particular VR, has been criticized for insufficient haptics and limited physical interaction for the development of motor-skills, well-needed in manufacturing [12,13]. Resulting in uncertainties of the transfer of the skills from the virtual training into the "real world" [14–16]. Using virtual training to address learning past the cognitive element of the learning curve in manufacturing has thus not been recommended [17]. Most XR training systems, thus prioritize simulation and visual fidelity over physical feedback and embodied live practice [18].

Solutions that improve physical feedback in XR training using haptic devices such as smart gloves exist but are yet not mature enough for satisfactory results and come at an additional cost and increased complexity [19]. Likewise, existing applications of welding XR trainings, like the existing Soldamatic welding simulator [20], require tailored XR equipment to provide physically realistic experience on generic and simplified welding tasks. Moreover, the weld simulator trainings are frequently designed for simulated environments, with simplified weld conditions and processes, not necessarily representative of the real task in mind [21].

This has led to a research gap of few demonstrated use cases of XR training targeting the full scope of technical skills training for real manufacturing tasks, including motor-skills components such as precise eye-tool coordination and dexterity [11]. Manufacturing XR studies remain heterogeneous in task type, objectives and hardware solutions. Moreover, recent reviews show that existing XR training research lacks sufficient anchoring in industrial use cases, failing to address industrial adoption. Suggestion for an emphasized focus on technology adoption, usability and user acceptance in manufacturing industry has thus been made [22].

This paper aims to close this gap by proposing an industrially deployable XR setup that can support early technical skill development requiring eye–tool coordination, real-tool handling, and repeated movement practice for dedicated manufacturing tasks. Furthermore, this paper seeks to investigate the user acceptance of XR technologies in technical manufacturing training using the Unified Theory of Acceptance and Use of Technology (UTAUT) framework. For this purpose, the following research questions have been stated:

RQ1. : How can technical skill training of manufacturing operators be supported using XR technology?

RQ2. : What is the user acceptance of XR technology in manufacturing training and skills development among shop floor workers?

The focus of the study is to evaluate the feasibility and usability of a XR training application for early technical skills training in manufacturing, thus it is delimited from evaluating long-term learning retention or application in running production.

The organization of this paper is outlined below. Section 2 introduces related work and state-of-the-art, presenting theory and studies relevant to interpret the results of this paper. Section 3 details the methodology used to answer the research questions, including the case study selection and design, software development, lab study and user study. Section 4 presents the results of tracking accuracy and performance measured in the lab study and Section 5 presents the results of usability and user acceptance from the user study. In Section 6 the results are discussed and answers to the research questions are provided while limitations of the study and aspects of future work are stated. Lastly, Section 7 concludes and summarizes the study.

2. Related work

Recent advancements on the hardware side of XR technologies, such as smaller standalone devices with rising computing power pushes a recent growth in XR training [22]. At the same time its ability to provide safe, repeatable and cost-efficient training environments, allowing trainees to practice on reals tasks without real-world consequences such as material waste, machine down time and safety concerns, increases the manufacturing industries interest [13].

Large amount of previous research highlights the strengths of XR training when it comes to task familiarization in manufacturing, following instructions and sequences for various manufacturing tasks, focusing on cognitive abilities [11]. However, less attention has been given towards training technical skills in manufacturing using XR [11], where eye-to-hand coordination, dexterity and motor-skills through repeated practice and hands-on experience is needed [23].

Martirosov et al. [15] confirmed that repeated practice and movements in XR training can result in the development of improved motor-skils as their study showed improved movement speed and accuracy over increasing training cycles in a VR glue gun training. However, the transferability of the technical skill learnt in the virtual environment to the physical task was found to be low due to lacking realistic haptics as the training was carried out on a virtual tool rather than the physical tool used in the real task.

For the sake of transferable technical skills in XR, haptics and physical feedback are shown to be of high importance [24]. Research has shown that the use of realistic haptics in XR training for manufacturing operators improves their situation awareness [25] and correlates with higher performance regarding accuracy in movement trajectories [26].

Ricca et al. [27] showed that multisensory feedback and haptics is more important than the virtual representation of the task itself, or of the interaction. They found that the virtual representation of the users' hand, interacting with a tool, had less effect on the training outcome

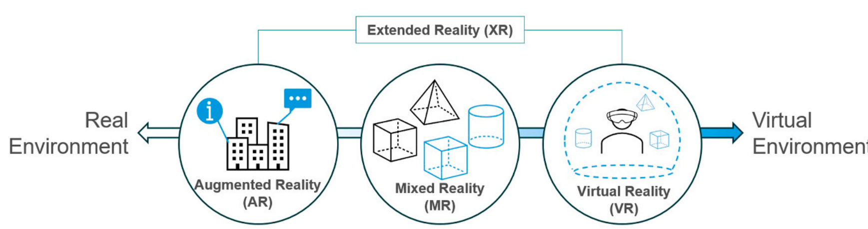

Fig. 1. The main XR technologies, presented on the virtual continuum spectrum.

compared to the tactile feel of touching the tool. Their study highlights that the presence of haptics and its interplay with the virtual environments is of higher importance than the virtual environment itself.

Meanwhile, Kaluschke et al. [28] showed that misalignment between the virtual representation of the tool and the physical object resulted in a negative impact on trainees learning performance, highlighting that hand-tool misalignment in the virtual training will negatively impact the transfer of the developed skills to the real world. Hence, sufficient virtual hand-tool alignment and physical feedback is crucial for the development of transferable technical skills. Similarly, Wang et al. [29], highlighted in their review that sufficient eye-to-hand coordination should be considered a key requirement for XR applications in manufacturing. At the same time, Hsiao et al. [30] have shown that virtual misalignment of up to 70 mm is in the range of the users' natural sensory biases. Thus defining the threshold of tracking accuracy of users' hands or tools that XR trainings needs to maintain to preserve the sense of eye-to-hand coordination.

The use of MR or AR, over VR, has shown to increase the sense of realism and knowledge acquisition in the training, which has been attributed to better multidimensional interaction between the virtual world and the real world, such as objects or tools [29]. Furthermore, previous research to replicate realistic haptics and physical tool interaction using props in XR for hand-coordination training in sports exist [10]. For instance, Chen-Chieh et al. [31] developed a VR training application for the correction of a golf swing, using physical golf clubs and a motion capture system.

Within manufacturing, previous use cases on technical skills training targeting motor-skills, in XR exists, although less predominant. Previously published literature reviews with the specific scope of manufacturing XR trainings from De Giorgio et al. [22], Radhakrishnan et al. [11], Eswaran and Bahubalendruni [32], Doolani et al. [33] and Ipsita et al. [12] have been consulted to get an overview of the existing literature on the topic of technical skills XR training in manufacturing. In total ten studies targeting motor-skills as the main objective of the training were found. These have been summarized in Table 1.

The referenced publications in the table above offer solutions with various degrees of virtual fidelity and physical realism for technical skills training in manufacturing. Dalle Mura and Dini [39] and Chuang et al. [40] proposed solutions using MR or AR, allowing the visual fidelity of real objects while the remaining publications relied on a fully virtual visual fidelity using VR. Likewise, various degrees of haptic fidelity were used in the solutions. Six publications offered solutions which let the trainee touch and interact with a physical object (e.g. a tool) during the training, while remaining four publications relied on fully virtual interactions without the presence of any physical haptic touch or feel.

For instance, Murcia-Lopez, Steed [37] developed a VR training for muscle memory and motor-skills in assembly, relying on fully virtual interactions when assembling products of various complexity. When comparing the developed VR training to paper-based training with a physical object, they found that the skill-transfer to the real world was lower in VR, although not statistically proven. Likewise, Martirosov et al. [15] used a fully virtual replica of a hand-held tool when training hand movements and could see that the transferability of the technical skill learnt in the virtual environment to the real world was low due to lacking realistic haptics.

Ma et al. [38] presented a solution of haptic feedback in VR assembly training using a haptic stylus pen, which introduced some haptic resistance and weight when performing an assembly training exercise in VR. Although the touch and feel of the haptic device did not realistically represent the shapes of the parts to be assembled, their findings showed that their solution could be used to predict operators motor-skill performance also in real assembly tasks.

Chuang et al. [40] was able to replicate realistic visuo-haptic feedback for training on a milling machine by overlaying a physical interaction with virtual corresponding elements. Two physical hand wheels were used together with virtual elements of a milling machine visualized in MR. As the trainee would turn the handwheels to control the milling machine, the virtual representation of the milling machine would update correspondingly while a set of magnetic brakes would generate realistic resistance and haptic feedback in the hand wheels. Their study showed that realistic haptic feedback increased the usability, as both training performance and user immersion increased with the increased haptic realism applied in the training.

Out of the ten papers listed in Table 1, four of them target tool handling and dexterity training for arc welding. Similar for all of these is that they use physical handheld tools, tracked by a purpose-built external tracking system, to replicate realistic tool handling and haptic feedback. Moreover, they all use a simulation engine and a display, or HMD, to visualize the resulting weld based on the tracked tool movements [34–36,41]. Commercial welding simulators that offer realistic haptic experience by utilizing full-size props of arc welding machines and physical electrode exists today and have shown promising results. Using a commercially available weld simulator, Byrd et al. [36] was able to determine expert users from novice users, indicating a high degree of realism and real-world transfer of technical skill.

However, these weld simulator trainings are typically purpose built for a few generic and simplified weld configurations in a simulated environment, not representing the actual welds that the user is expected to perform in live production. Heibel et al. [21] shows in their review that a gap still exists in incorporating multiple different weld configurations, conditions, processes and positions, in the simulator trainings that would more realistically represent the real tasks. Moreover, sensory fidelity is often limited by tracking accuracy and visual fidelity [21].

Building on the related work presented in this section, this paper aims to further advance the research area by proposing an industrially deployable XR setup that can support technical skill development requiring precise eye–tool coordination, real-tool handling, and

Table 1
Related work of manufacturing XR training targeting technical skills training with motor-skills components.

Paper	Goal of Training	XR Tech	Hardware	Physical Interaction	Haptic feedback	Environment	No. Participants
[34]	Manual arc welding skill training	VR	Desktop PC	Yes	Yes	Lab	na
[35]	Manual arc welding skill training	VR	Desktop PC	Yes	Yes	Lab	6
[36]	Manual arc welding skill training	VR	VRTEX 360	Yes	Yes	Industrial	49
[37]	Assembly training and transfer of motor-skills	VR	HTC Vive	No	No	Lab	60
[38]	Assembly training and transfer of motor-skills	VR	NVIDIA® 3D Vision	Yes	Partly	Lab	36
[15]	Tool handling training and transfer of motor-skills	VR	HTC Vive	No	No	Lab	16
[39]	Panel alignment of car body assembly training	AR	*HMD Not specified*	Yes	Yes	Lab	na
[40]	Milling force feedback training of operator	MR	HoloLens 2	Yes	Yes	Lab	31
[41]	Manual arc welding training	VR	HTC Vive	Yes	Yes	Lab	15
[42]	Motor-skills training for drilling operator	VR	Meta Quest 2	No	No	Lab	na

repeated movement practice in a non-simulated, real manufacturing tasks. Furthermore, this paper evaluates its usability and user acceptance from an industrial context, taking the research one step closer to industrialization.

3. Methodology

To answer the stated research question, a case study with an automotive case company was conducted. The industrial case study allowed the study to be performed together with its intended end users in a probable scenario for its future use, giving more direct insights into its potential usefulness in a manufacturing context [43]. An XR training application was developed by the authors for the purpose of the selected case and later tested in two studies, a lab study and a user study. The usage of multiple studies and data collection methods was seen as complementary to each other and used to strengthen the results and discussions later held to answer the research question [43]. The lab study aimed at evaluating the technical capabilities and accuracy of the developed XR training, while the user study, through both surveys and interviews, aimed at evaluating the user acceptance and its perceived usability by its end users and subject matter experts following the UTAUT model. The overall research methodology is illustrated in Fig. 2, providing an overview of the steps required to replicate the study. The steps of the methodology were selected to address the RQs in terms of evaluating both the technical feasibility, usability and user acceptance in an industrial setting. This approach allowed for the integration of both qualitative and quantitative data to support the findings and recommendations in this study. Inspiration to the methodology was taken from Schlenker et al. [44]. The following subsections will further detail each step of the methodology as shown in Fig. 2.

3.1. Use case selection and requirements

The use case at Volvo Car Corporation focused on the training of operators in manufacturing areas where sealant is manually applied to car bodies. The purpose of the applied sealant is to create a protective barrier against water along seams and flanges of joined car body parts. While a substantial part of these operations are automated, manual operations are still carried out by operators in areas where it is challenging to automate. To ensure proper seal and protection, high accuracy of the placement of the sealant is required. For instance, a sealant bead with a width of 4–14 mm is typically industry standard for aesthetic and water sealing purposes [45], thus implying that an error margin of only a few millimeters can compromise the seal. This in combination of intricate geometries of the sheet metal flanges and seams puts high requirements on the operators' technical skills such as tool

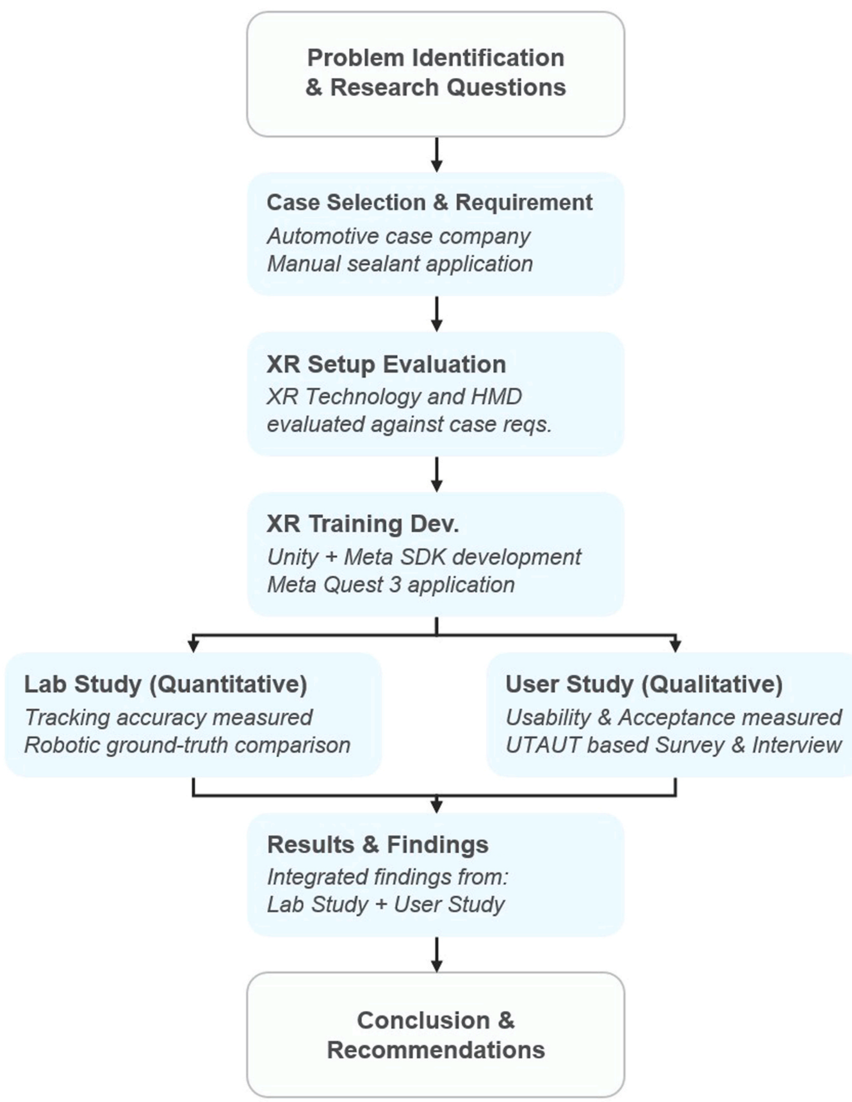

Fig. 2. Flow diagram outlining the steps of the research methodology used.

handling and precision.

The manual sealant is applied using a handheld sealant gun that channel sealant material out of a thin nozzle. When activated, the operator needs to move the nozzle at constant speed and with a steady hand over the seam or flange to be covered. This operation requires the operator to handle the tool with high precision and speed as the quality of the seal is subjected to the operator's force, positioning of the nozzle and speed. From the company's perspective, few stations are as demanding from a technical skills perspective as the manual sealant stations, as most other high precision tasks have been automated. The particularly high requirements on the operator's technical skill in terms of tool handling made the manual sealant task especially relevant for this study. See Fig. 3 for an illustration of the task selected for the case study.

Currently the operators are trained over a period of weeks but vary depending on individual progress. Typically, training starts in a general training facility, where operators practice tool handling regarding positioning, speed, and angle of the nozzle on simpler seams and flanges especially developed for training purposes. When they have reached a sufficient level of accuracy, the operator moves on to train on real operations using a real car body at dedicated training stations inside the factory until they are ready to partake in the live production. During most of the training, real sealant material is used. Thus, resulting in wasted material, as well as extensive time spent on cleaning and removing applied sealant material from the workpiece before starting a new training cycle. Thus, potential business value of reduced material waste, scrap, training and changeover time motivated the case from the case company perspective.

By evaluating the technical and operational feasibility, as well as the user acceptance of a complementary XR solution for sealant training, the case company expects to make a go or no-go decision for further pilot implementation. The scope of the case focused on early motor-skills development and familiarization through an XR training application to be used at the current sealant training stations. Thus, the existing training material and procedure at the training stations were to be replicated and used for the development of the XR application.

Considering the uniqueness of each flange, special nozzles and movement patterns are required for every performed seal, and operators would regularly require continuous training as new car models and flanges were introduced to the line. For this purpose, existing commercial virtual training solutions were deemed insufficient, as they lacked the task specific conditions and flexibility to scale over multiple seals and products. Thus, a completely flexible and scalable solution was requested.

3.2. XR Training development

As the nature of the tasks required precision tool handling, maintaining a realistic physical feeling and haptics when interacting with the tool in the XR training was crucial. For this purpose, the use of physical props, as opposed to a controller, have been recorded to have significant impact on realism, immersion and performance [46]. A decision was thus made early on to include the real sealant tool and a physical car-body as part of the XR training. This meant that the application needed to monitor the translation of both the physical car body and tool to properly map them to any virtual elements. To overcome this challenge, several trials were performed with various XR devices to select the most promising device or technology capable of meeting this requirement.

Fig. 3. Operator applying sealant to the D-pillar of a car body.

Trials using an HTC Vive VR headset and HTC Vive trackers, attached to the tool and car body, were conducted but ruled out due to insufficient accuracy when tracking the physical props. This resulted in a mismatch of the visual perception in the VR and the physical interaction of the tool creating it difficult with hand-to-eye coordination for precision tasks. As maintaining sufficient eye-to-hand coordination is essential for the development of motor-skills [28], this solution was deemed out. A second trial was carried out in AR using Microsoft HoloLense 2 and the PTC Vuforia engine for visual tracking. QR codes were mounted on the car body and the tool to be tracked by the headset. The AR headset enabled better eye-to-hand coordination as the physical car body and tool was visible at all times though the transparent display, but due to poor visual tracking under rapid movements the tracking was often lost or frequently lacking behind the movement of the tool. This resulted in it being ruled out as a feasible solution. Finally, the decision was made to go forward with an MR solution using a Meta Quest 3 headset and its passthrough functionality. The passthrough camera feed of the headset was deemed accurate enough to ensure good eye-to-hand coordination while the built-in tracking system of the headset allowed tracking of rapid movements.

The solution was developed in the Unity 3D game engine together with the Meta XR SDK. The SDK allowed access to the camera feed of the headset enabling the passthrough functionality while enabling hand- and controller-tracking. One of the controllers was attached to the sealant tool using a customized 3D printed attachment, and the tool center point (TCP) of the sealant tool could be calculated with an offset from the controllers attach point. The TCP of the sealant tool could then be accurately tracked, and its position and rotation were saved to an array every 5 mm. The 3D printed attachment also interlinked the trigger of the sealant tool to one of the buttons of the attached controller, making it possible to affect the state of the button by pressing the trigger of the physical tool. When pressed, a line with sealant-like color and characteristics is drawn between the most recent, and current, TCP position to illustrate the applied sealant using the LineRenderer component of the Unity library. This created the illusion of a virtual sealant line, apparent to the wearer of the Meta Quest headset. See Fig. 4.

Moreover, the position and rotation data of each TCP point saved could be compared against a benchmark to score the trainee on their performance, taking into account the accuracy of the tip placement, speed, and rotation of the tool, when applying the sealant. At first, hard-coded tolerances were set based on position data from the CAD of the car body and estimates of requirements from sealant experts from the case company. However, these hard-coded benchmarks reduced the flexibility of the solution as it would require constant updating of the training application as car models and variants changed over time. Instead, a feature was proposed to enable live editing of the benchmarks within the application itself.

The feature allows an experienced operator or trainer to "record" a benchmark using the Meta Quest 3 headset. When turned on, the feature will record the sealant line drawn by the trainer and store its TCP position, rotation and speed as a benchmark, as these are currently the metrics used in the assessment of the current training. When handing over the headset to the trainee, the recorded sealant line will show up highlighted in red, indicating the guideline that the trainee would try to replicate. The stored TCP data would then be used as the benchmark values to score the trainee against. See Fig. 5.

Furthermore, a feature to recalibrate the TCP position was implemented to allow for flexibility to change the nozzles of the sealant gun.

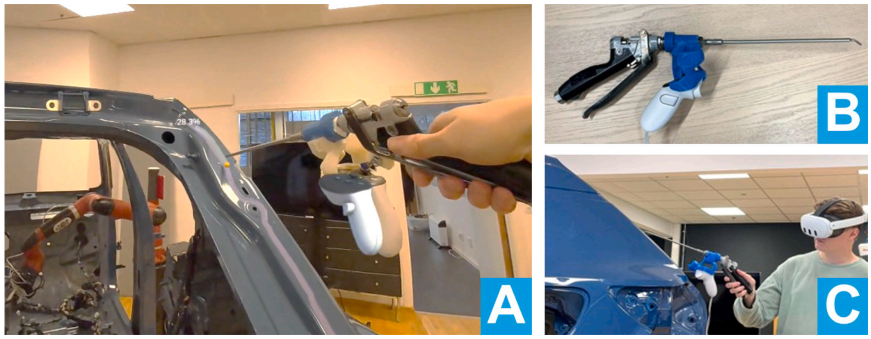

Fig. 4. Pictures of the created MR sealant training. (A) Point-of-view from the trainee when applying the virtual sealant. (B) The sealant tool used and the attached controller for tracking. (C) Trainee engaging with the MR sealant training on a car body.

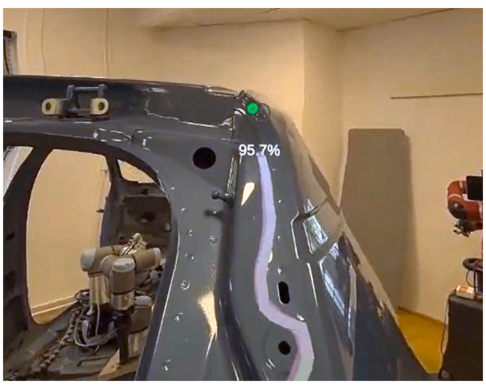

Fig. 5. Point-of-view from the trainee showing the scoring of the applied sealant.

When the feature is turned on the user can calibrate the new TCP position by using the joystick on the Quest 3 controller to manually move the TCP in the application, visualized by an orange sphere, until it is aligned with the tip of the new nozzle. In this sense, complete flexibility of the solution is secured, allowing both multiple sealant nozzles to be used and allowing the trainer to continuously record new sealant lines as benchmarks. This ensures that scalability of the solution over multiple products, tools and use cases is provided.

To provide a structured overview of the implementation, the system architecture of the developed MR training application is presented in Fig. 6. The system combines a Meta Quest 3 headset, utilizing inside-out tracking and passthrough-based mixed reality, with Unity-based processing through the Meta XR SDK. This enables real-time tracking of the sealant tool, calculation of the tool center point (TCP), and subsequent visualization and performance assessment within the training application.

The developed XR training preserved the physical realism of the training by incorporating the real tools and workpieces (e.g. car body) used in the current training but eliminated the need for real sealant material to be used, as this now could be visualized virtually in the HMD by the tracing of the tools TCP. Furthermore, by virtually tracking and storing the TCP positions, angles and speeds, real-time feedback can be provided directly to the trainee.

Utilizing the existing spatial tracking and controller tracking, enabled by the Meta Quest 3 and the Meta XR SDK, no external tracking system or setup is required. Furthermore, the use of the real sealant tool and workpiece (e.g. car body), together with the possibility to record and create custom trainings and benchmarks within the XR application itself, enables real manufacturing tasks and products to be used as the basis of the training. Which distinguishes the solution from previous purpose-built XR simulation training for generic scenarios (e.g. welding).

3.3. Lab study

To ensure eye-to-hand coordination and the possibility of transferable motor-skills, sufficient accuracy and reliability in tool tracking was needed. Since tracking accuracy depends on real-world conditions, environment, and application, general datasets on tracking solutions are not fully sufficient and use case specific quantitative evaluations should be considered [47]. Therefore, a controlled experimental setup was designed to accurately measure the tool tracking accuracy of the XR training while closely replicating the real sealant training conditions.

The experiment utilized a Meta Quest 3 headset, the XR training application, and a physical sealant tool, which was mounted onto a UR3 robotic manipulator. The robot served as a ground-truth reference system due to its high positional repeatability ($\pm$0.03 mm) [48]. The TCP of the sealant tool was carefully calibrated to coincide with the robot's TCP using a fixed mounting fixture to eliminate relative movement between the tool and the robot.

The UR3 manipulator was programmed to execute three predefined trajectories consisting of multiple waypoints, see Fig. 7. These trajectories were designed to mimic realistic sealant application paths, and the speed of the manipulator was 200 mm/s to best represent the speed of the real sealant task. Each trajectory was repeated five times, resulting in a total of 15 trials.

The Meta Quest 3 headset was mounted on a stationary stand at a distance of approximately 100 cm from the base of the robot, corresponding to a typical user viewpoint during training. The environment remained static throughout all trials, with consistent lighting conditions and no occlusions, to minimize external influences on tracking performance, see Fig. 8.

During each trial, the XR application tracked the position of the sealant tool's TCP and recorded it as time-stamped Cartesian coordinates (X, Y, Z), which were exported as CSV files. Simultaneously, the ground-truth TCP positions were obtained from the robot controller based on its programmed waypoints and coordinates in relation to the (0,0,0) origin of the robot's coordinate system. Both datasets were expressed in their respective coordinate systems, and alignment between coordinate frames was ensured through prior calibration of the tool and reference positioning.

Tracking accuracy was evaluated by comparing the distances between consecutive waypoints in the XR-tracked data with those from the robot ground-truth data. The tracking error was defined as the absolute deviation (in millimeters) between these distances. A tolerance of $\pm$0.03 mm was applied to the ground-truth measurements, reflecting the manufacturer-specified repeatability of the UR3 robot.

This methodology, adapted from Pereira et al. [47] and Schlenker et al. [44], enables a direct quantitative comparison between XR-tracked motion and high-precision robotic ground-truth under controlled and repeatable conditions.

The results from the study were later discussed and compared to the limit values of visuo-proprioceptive by Hsiao et al. [30] to ensure

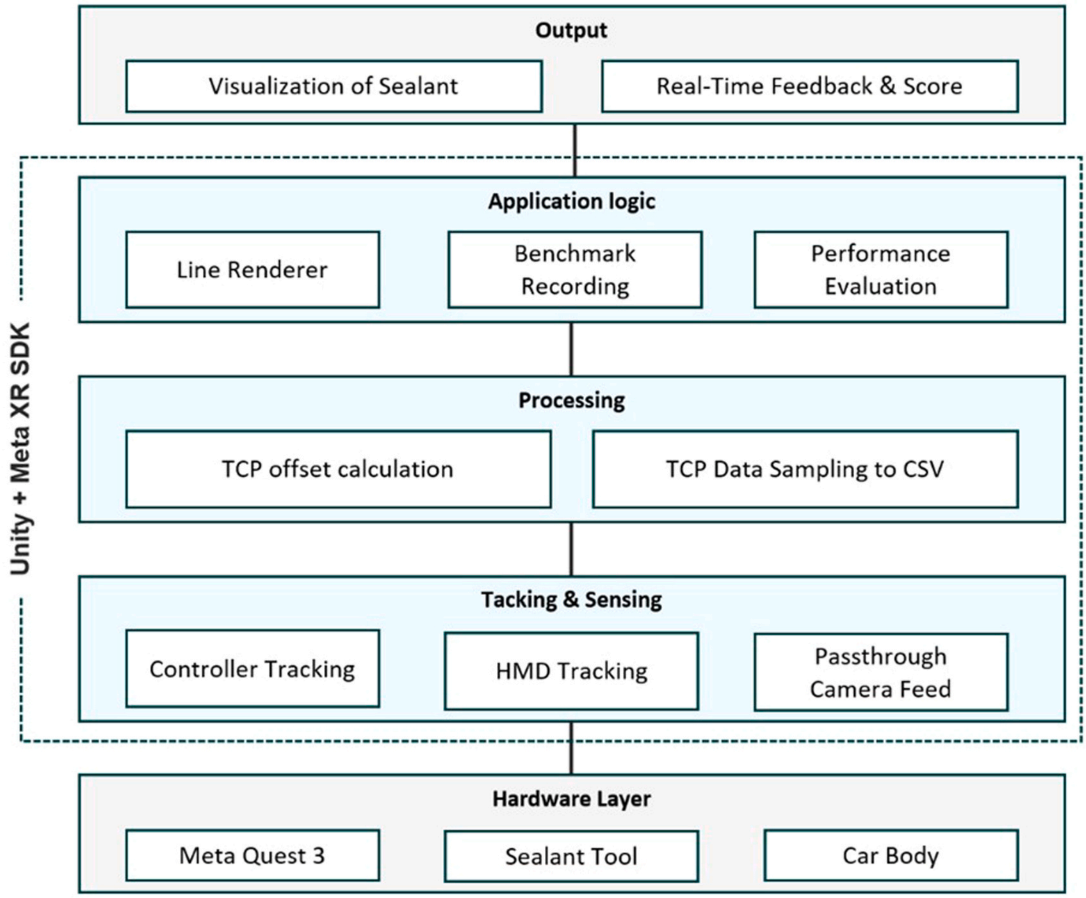

Fig. 6. System architecture of the developed XR training.

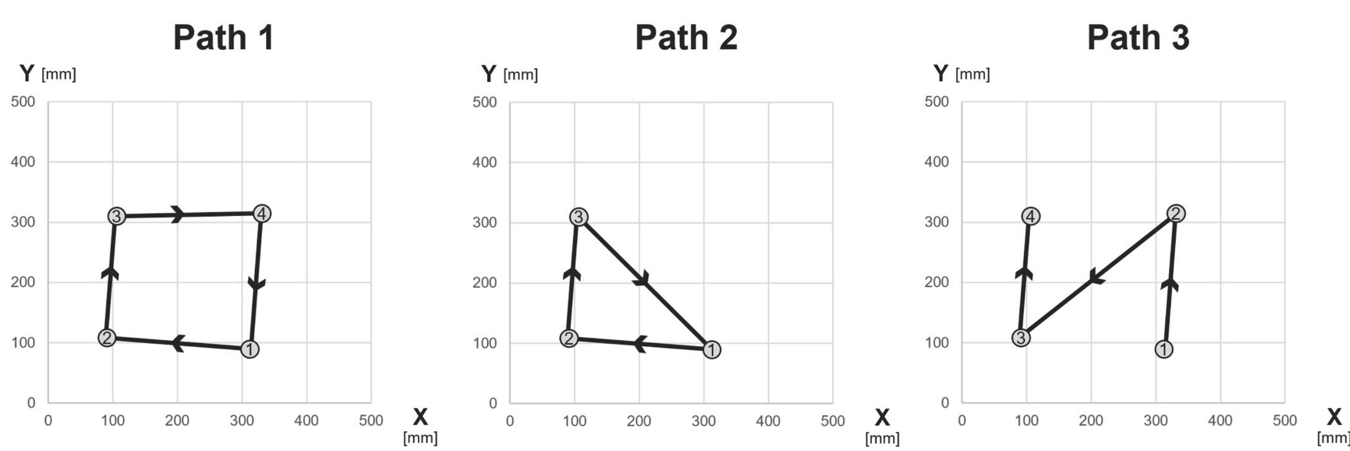

Fig. 7. Representation of the TCP paths used for the experiment.

eye-to-hand coordination, and specifications of sealant applications [45] to determine its use for precise sealant application training.

3.4. User study

To better understand the usability and the user acceptance of the developed solution in the context of the intended training task, a user study based on the UTAUT framework was conducted with existing sealant operators at the case company. In total 45 sealant operators from two factories, one in Belgium and one in Sweden, volunteered to participate in the study. The study took place during two separate instances, in May 2025.

For the on-site tests, a training scenario was prepared based on the current training setup at the case company. Existing training stations at each of the plants were used for the test together with a real car body normally used in the training. The training scenario created for the study was on adding sealant to a sheet metal seam located on the D-pillar of one of the case companies' car models, following the current practice in the factory. The setting of the on-site test was replicated to be as similar to an actual training scenario as possible with the same equipment, station and car body as would be used in the actual training. Moreover, a trainer from the case company was present during the entire test to

Fig. 8. Setup of the study using the UR3 and the Meta Quest 3.

guide the participants through the training and to ensure that the training was performed as expected in reality.

The participants arrived one-by-one with an interval of 30 min to the training stations where they were given a short introduction to the study to clarify its purpose and process. All participants were then asked to fill out a pre-questioner form to capture their consent of participating in the study as well as being given the option to opt out of any voice or video recordings during the test. The pre-questionnaire form also included questions of demographics, experience and previous XR usage. Each participant then tested the XR training application under the guidance of one of the trainers of the case company for a maximum of 15 min before being asked to fill out a post-questionnaire form and participating in a closing interview. See Fig. 9 for an overview of the user study procedure.

3.4.1. Participants and sociodemographic

The participants in the study were recruited among the current sealant operators employed by the case company based on the selection criteria that they had previously completed the current sealant training at the case company. In the context of the use case, the existing sealant operators of the case company, having the most experience with the task, were considered as subject matter experts and thus deemed the best user group to test and evaluate the usability of the solution. Based on their experience of working with manual sealants on a daily basis and their experiences from their own past training, the sealant operators were able to evaluate the solution and its potential as a replacement or complement to their normal training routine.

A total of 45 operators participated in the study, 26 employed at the factory in Sweden and 19 employed in the factory in Belgium. A majority of 30 participants were male while 14 were females. Ages spanned from 18 to 60 with the majority of 30 participants being younger than 35 years old. Likewise, the experience of the operators also varied with 16 participants having more than five years' experience working with sealant, while ten participants were new hires with less than three months' experience. The overall XR experience among the participants was low with 32 participants who responded to have never tried any XR device before and only four participants reported the use of XR devices more than ten times. See Table 2 for a full breakdown of the socio-demographic and experience level of the participants.

Table 2
Table presenting the sociodemographic data of the participants.

Category	Alternative	Number of answers	% of answers
Gender	Male	30	67%
	Female	14	31%
	Other / Prefer not to disclose	1	2%
Age	18–24	12	27%
	25–34	18	40%
	35–44	8	18%
	45–55	5	11%
	> 55	2	4%
Country	Sweden	26	58%
	Belgium	19	42%
Work experience	< 3 months	10	22%
(Sealant)	3 months – 1 year	4	9%
	1–3 years	9	20%
	3–5 years	6	13%
	+5 years	16	36%
Previous XR use	Never	32	71%
(Incl. VR, MR, AR)	1–3 times	6	13%
	3–10 times	3	7%
	10–50 times	2	4%
	+50 times	2	4%

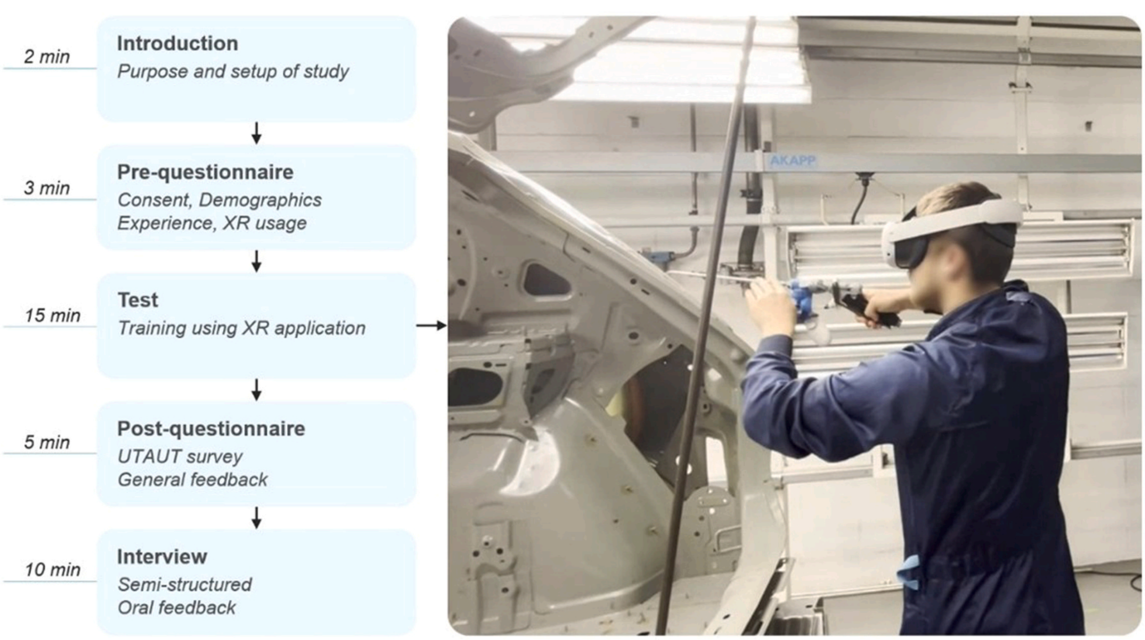

Fig. 9. Overview of the user study procedure and picture of one of the participants carrying out the test of the XR sealant application in the factory in Belgium.

3.4.2. Survey

After testing the training application, the participants were asked to fill out a survey to evaluate their experience. The survey consisted of two parts, one part capturing input related to the UTAUT framework [49] and one part for general feedback. The UTAUT theory helped to understand the driving forces for user acceptance of a technology based on the constructs of *Performance expectancy* (PE), *Effort expectancy* (EE), *Social influence* (SI) and *Facilitating conditions* (FC) [49]. It was selected due to its wide adoption for predicting emerging technologies usability and user acceptance across domains especially within training and education technology [50] and XR [51]. Moreover, aligned well with the purpose of the user study of predicting user acceptance as a complement to the already conducted technical evaluation in the lab study. A five-point Likert scale was used to capture input on 6 questions under the construct of PE, EE and SI according to the UTAUT theory. FC, as per the UTAUT framework, was not included in the survey as its focus is on evaluating the internal infrastructure to support the facilitation of the technology [49], which was not in scope of this study and research question. The second part of the survey consisted of three additional five-point Likert scale questions and three open-ended questions to capture general feedback from the experience and suggestions of improvements on the solution. Table 3 displays the questions posed to the participants in the survey.

3.4.3. Interview

Before leaving, the participants were invited to a closing interview. The interview was semi-structured and held by one of the authors. Open questions based on the UTAUT framework and general feedback on the experience were prepared in advance, but spontaneous follow-up questions occurred to keep the conversation open and allow for more in-depth discussion [52]. With consent from the interviewees, previously captured in the pre-questionnaire, the interviews were recorded for transcription and analysis purposes.

The transcription of each interview was systematically studied and thematically analyzed to be coded according to the categorization of the UTAUT constructs (PE, EE, SI). A deductive approach to code the interviewees responses towards initially perceived categories of responses was used [53]. If no already defined responses were identified as a good match, a new unique category of responses was established [54]. After some iterations the authors reached a level of saturation where no new unique responses per question were needed as all the interviewees' responses could be labeled into existing categories. The thematical analysis approach was selected due to it commonly being used in qualitative research and ability to adapt to most research fields and questions [54].

Table 3
Questions used in survey.

Category	Question	Name
Performance Expectancy (PE)	I think real sealant applications can be taught using the XR training	PE1
	I think the XR training is more effective than the traditional training for learning	PE2
Effort Expectancy (EE)	I think using the XR training application was easy	EE1
	I think the instructions provided in the XR training were easy to follow	EE2
Social Influence (SI)	I think it would be motivating and fun to use the XR training application in my training	SI1
	I think my confidence would increase by using the XR training application	SI2
General feedback	How similar did you find the XR training experience compared to the real sealant application?	GF1
	Would you have appreciated using the XR training as part of your own training when you started with sealant?	GF2
	How would you rate the overall experience of using the XR training application for learning manual sealant?	GF3
Open answer	Do you have any suggestions on when and how such XR training applications should be used during the sealant training?	GF5
Open answer	Did you encounter any issues during the use of the XR training application? If so, what kind of issue did you encounter?	GF4
Open answer	Do you have any suggested improvements to the XR training application that would have enhanced the learning experience?	GF6

4. Lab study results

The lab study provided quantitative insight into the tracking accuracy of the XR sealant training application. The tracking error was calculated as the deviation in distances between the waypoints measured by XR system and the ground-truth positions provided by the robot. The measured tracking errors can be seen in Table 4 below and are expressed in mm.

The average tracking error across all three TCP paths and cycles was approximately 7.7 mm as seen in the box plot of Fig. 10. However, errors in individual segments varied, with some outliers, most notably the highest error of 21.4 mm. The largest errors tended to occur at the beginning and end position of each TCP path. This is most likely due to the start motion recoil and other manipulator-related delays. The error rate was also slightly higher when the robot came to stop, this most likely due to latency in the XR system's data capture or settling down of the manipulator when it came to stop.

While the average tracking error is slightly higher, it is still consistent with findings from similar XR tracking studies using robotic arms for ground-truth benchmarking. For examples [47], and Schlenker reported millimeter-level accuracy for XR systems under controlled conditions, with occasional outliers due to system or environmental factors.

As described in Section 3.2, the XR training application used in this experiment only updated its TCP position every 5 mm, along the sealing line. Meaning that the granularity of the software was limited in itself to a minimum average tolerance of 5 mm. The higher measured average tracking errors of 7.7 mm emphasize the need to also consider system latency and environmental conditions as contributing factors to the tolerance of the system.

5. User study results

This section presents the results of the user study carried out with the 45 participants at the case company. First an overview of the UTAUT survey results and is presented followed by sub-sections with more detailed results of each of the constructs of *Performance expectancy* (PE), *Effort expectancy* (EE) and *Social influence* (SI). The sub-sections bring deeper insight from both the survey and interview study which are presented jointly.

Aggregated results of the first part of the survey and the constructs of PE, EE and SI, as per the UTAUT framework, are presented in Fig. 11. The results indicate the influence and driving force of each construct towards the user acceptance of the technology and its implementation. The results show that 58% of the participants responded positively towards expected increased learning performance (PE) using the XR training platform, meanwhile 21% of the participants were uncertain about its effect on the learning performance and 20% responded negatively towards the expectation of an increased learning performance. The aggregated results of the questions behind the EE construct show that 76% of the responses points towards that the efforts needed to learn and use the XR application are low, while 16% were uncertain about the needed efforts and 9% thought that it would require high efforts to operate the XR application. Lastly the aggregated results behind the SI construct show that 88% of the responses indicated that the participants felt motivated and encouraged to use the XR training application in their training while 10% were uncertain and 2% were negative towards the

Table 4
Table of the measured tracking errors in mm per measured distance and cycle.

TCP Path	Measured distance	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Error Avg.
Path 1	1–2	1,162716	−1,88638	−16,0879	−8,9454	−13,3383	−7,819045
	2–3	−2,05096	−0,66083	−9,06414	−5,38798	−0,64677	−3,562137
	3–4	3,846856	−11,8389	−2,88194	−8,96464	−2,81627	−4,530972
	4–1	−16,4732	−4,69626	−11,2139	−9,93991	−21,3956	−12,74378
Path 2	1–2	−10,2331	−10,7513	−6,05816	−7,20132	−6,10925	−8,070625
	2–3	−2,10991	−8,17303	−6,51357	−9,06782	−1,25223	−5,423311
	3–1	−6,85246	−15,0449	−13,4106	−3,50971	−11,4846	−10,06043
Path3	1–2	−7,77486	−13,7513	−6,23311	−6,92312	−9,61729	−8,859933
	2–3	0,433894	−1,3739	−0,67867	−2,77182	−1,27551	−1,133200
	3–4	−15,7812	−12,1536	−14,0027	−13,8831	−16,6731	−14,49876

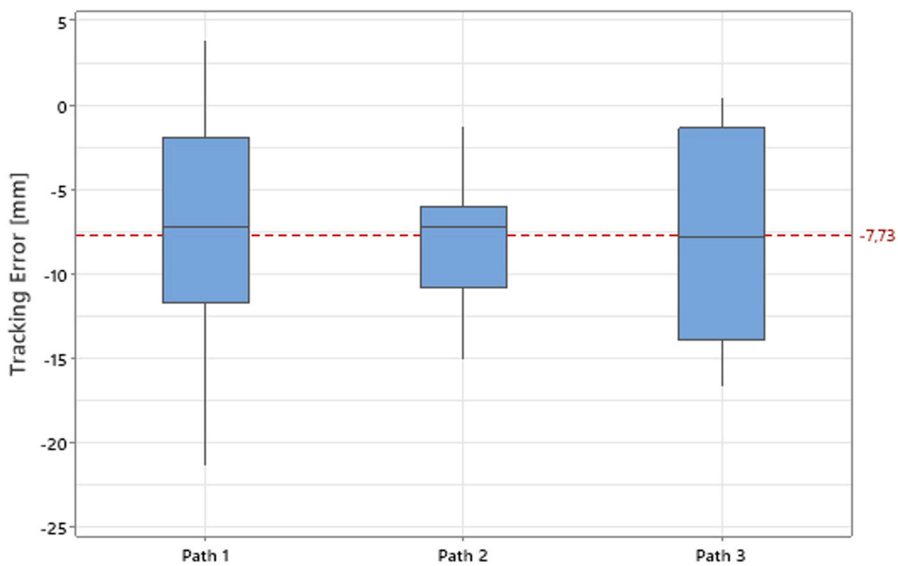

Fig. 10. Boxplot of tracking errors for the three TCP paths.

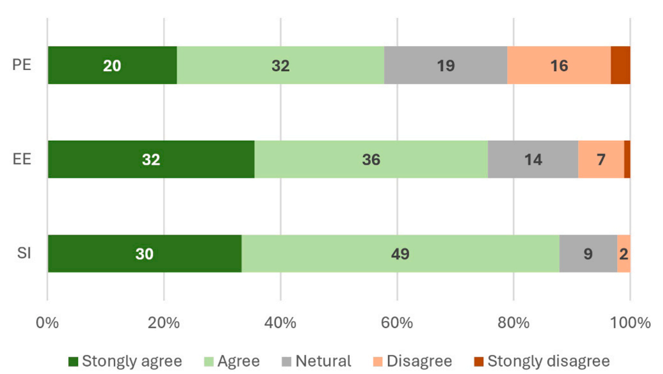

Fig. 11. Overview of the aggregated survey results of the UTAUT constructs in scope.

motivation to use such an XR application.

The results show that the construct of SI received the highest score while the construct of PE received the lowest score, indicating that the expectations on the social influence and the motivation to use the XR training application (SI) exceed the expected increased learning performance (PE) by the participants. To further explore the data a transformation of the results from the five-point Likert scale to numeric values of 1–5 was done, where 1 represented “Strongly disagree” and 5 represented “Strongly agree”. The average, median and standard deviation of each construct can be seen in Table 5. A T-test later showed that statistical difference ($p > 0.05$) was found when comparing PE with both EE ($p = 0.078$) and SI ($p = 0.001$). Meanwhile, no statistical difference was found between EE and SI ($p = 0.127$). Confirming that the expectancy by the participants on the increased performance (PE) is statistically proven to be lower than the expected lowered effort (EE) and social influence (SI) as the main driving force for the adoption of the XR training application.

Table 5
Average, median and standard deviation of the results of each construct.

Construct	Average	Median	Standard deviation
Performance Expectancy (PE)	3,56	4	1,12
Effort Expectancy (EE)	3,99	4	1,02
Social Influence (SI)	4,19	4	0,7

5.1. Performance expectancy

Although PE was statistically lower than both SI and EE, a majority of the participants in the user study still saw expected performance benefits in terms of improved learning experience using the XR application, as indicated in both the survey and the interviews. In total, 32 participants (71%) responded that they expected that the XR training could be used to develop skills that would transfer to the real physical task, while the remaining 13 (29%) saw it as unlikely or were uncertain to its effect on the learning. See Fig. 12.

In regard to the effectiveness of the training a total of 20 participants (45%) responded that the XR training would result in a more, or much more, efficient learning experience compared to the traditional physical

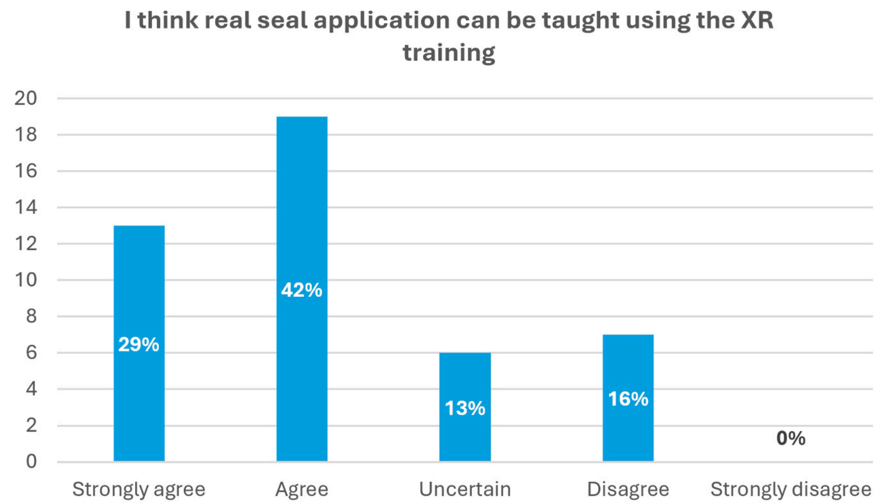

Fig. 12. Survey result of the expected skill transfer to the physical task.

training. Another 13 participants (29%) thought that the XR training was as effective in teaching the skill, while 12 participants (26%) responded that the XR training was less, or much less, efficient than the physical training. See Fig. 13.

From the interviews it could be seen that, among those that indicated an expected increased efficient learning experience using XR in the survey, pointed out the reduced cleaning time of live sealant material as the main contributor towards its effectiveness. In total, 20 (44%) out of the interviewed sealant operators indicated in their interviews that by eliminating the time needed for cleaning sealant material in between the training cycles, a higher number of training cycles and repetitions was expected when using the XR training. At the same time 16 (35%) sealant operators also expressed consequential effects of reduced waste of sealant material, typically used in the training, as a benefit from a cost or environmental perspective.

When questioned about the possibility to learn in XR, 29 (64%) of the participants addressed the possibility of training several key aspects of the job task using the XR application. In particular, 18 (40%) participants mentioned the ability to learn the movements regarding proper tool handling and body movements. Here, the ability to do a higher number of movement repetitions was seen positively affecting the ability to build muscle memory at a faster rate. Moreover, 12 (26%) participants explicitly mentioned the possibility to get enhanced "feeling" and dexterity for the task early on in the training. Here, the possibility of training with the real tool on a realistic scenario from day one of the training was seen as shortening the training time. Lastly, 5 (11%) interviewees pointed out the system's ability to give feedback to the user on errors and improvements as an advantage of the system that would improve the understanding and the performance of the trainee. See Table 6 for some representative quotes from the interviewees regarding the expected improved performance.

Among interviewees that did not foresee any improved performance or learning outcome from using the system, the majority pointed out the lack of realism and accuracy of the solution as its limitation that would hinder efficient skill acquisition. Similar findings were captured in the general feedback from the survey, where eight participants (18%) responded that the experience from the XR training was dissimilar, or very dissimilar, compared to the real sealant experience. Another 17 (38%) responded that the experience only was somewhat similar and a minority of 20 (44%) participants responded that the experience was similar, or very similar. In the interviews several participants point out the lack of realistically simulating the fluid properties of the real material as its limitation, e.g. P26: "*The real fluid sealant is acting differently, not sure if this is accurate enough*". P19 also pointed out the lack of realism in the simulation but at the same time acknowledged its use among new employees - "*For experienced operators it is not realistic, but maybe it is*

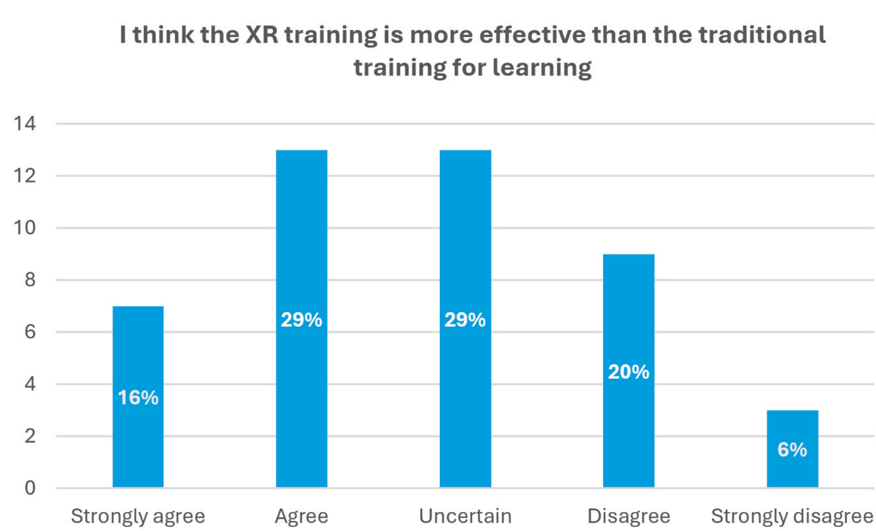

Fig. 13. Survey result of the XR learning experience effectiveness on the training.

Table 6
Most representative quotes advocating for increased performance expectancy.

Performance Expectancy	*Most representative quote(s)*
Effective training time	**P7:** "*Today we spend more time on cleaning than on practicing, this (XR) gives us more time in the day to train. That is good.*" **P12:** "*In the VR it does seem to be a lot easier to clear everything up and you're probably going to be learning a lot quicker.*" **P16:** "*I see how this will make it easier to teach someone, because you don't lose time in the training when you need to clean and wipe off the sealant.*"
Skill acquisition	**P32:** "*This is really good to practice the movements and to start building the muscle memory… when you enter the factory afterwards to do real sealant you will learn the real job much quicker*" **P39:** "*I think it will help the trainees to get the feeling and the movements of how to handle the tool*"
Support and feedback	**P8:** "*You can see directly the results on what you are doing*" **P12:** "*The system will tell you how well you are performing*" **P21:** "*(in traditional training) you can do a seal, and you won't know if you have done it well or not, or what you did wrong, with this you will get some feedback to help you.*"

enough for new employees to learn about the job and to try it".

5.2. Effort expectancy

The efforts connected to the usage of the XR training amongst the participants were considered generally low. A clear majority of 33 participants (73%) reported it as easy, or very easy, to use the XR training application, while six participants (13%) reported issues or difficulties in using the XR training. See Fig. 14.

As the majority of the participants did not report any issues or difficulties in using the XR training, few of them also raised any concerns in the follow-up interviews. Overall, a positive tone towards the ease of use was conveyed in the interviews, apart from the six participants that raised issues regarding unfamiliarity with the hardware, low resolution and motion sickness. See Table 7 for some representative quotes from the interviewees regarding the expected effort of use.

5.3. Social influence

Regarding the social motivation and willingness to use the XR training application 29 (64%) of the participants responded in the survey that they were likely, or very likely, to appreciate the use of the XR training application during their own training, while eleven (24%) responded neutral and five (11%) responded unlikely to have appreciated the use of the XR training. Moreover, 39 participants (86%) made remarks that the XR sealant training was more motivating and fun to use compared to the traditional training indicating a positive attitude towards using the XR training. The remaining six participants (13%) did not see any added motivation to use the XR training compared to the traditional training. See Fig. 15.

Table 7
Most representative quotes regarding the expected effort of usage.

Effort Expectancy	*Most representative quote(s)*
Ease of use	**P5:** "*The headset was easy to use and adjust for my size.*" **P20:** "*It was easy even if it took some time to get used to.*"
Low resolution and visuals	**P9:** "*Resolution and picture was too bad in order to see where I should place the tip (of the sealant gun)*" **P13:** "*It was a bit difficult to see where to place the sealant line*"
Unfamiliar hardware	**P2:** "*It was difficult to understand how it worked in the beginning… I would need training just to understand the training software*" **P35:** "*I am not used to the technology, so it took me some time to understand how it worked and how to use it*"
Motion sickness	**P38:** "*I was a bit sensitive to the motion*" **P18:** "*I think that being able to see the real car (pass-through) helped me not to get as sick as I have been before in VR*"

Although most of the participants responded positively towards their own motivation for using the XR training, there was a consensus in the follow-up interviews that the technology and application would be especially attractive among younger people and new hires. The younger generation's ability to quickly adopt new technology was mentioned but moreover some socially motivating factors were also raised by the participants. The most frequently mentioned was the reduction of the stress level that is associated with being new, young and inexperienced. Several participants mentioned stress and fear of making a mistake in front of your supervisor and team during the training and suggested that the XR training would provide a safe space for mistakes to occur without consequences. In the survey responses similar reasoning could be observed as 40 participants (88%) responded that the XR training would improve the confidence level of the trainees when entering the factory for the first time. See Fig. 16.

Lastly, three participants addressed in their interviews the reduced risk of personal harm as another socially motivating factor for the use of the XR training. Injuries have occurred in the past due to improper tool handling by new employees resulting in sealant splashing into the eyes of the operators. The trainee, and operators in close vicinity of the trainee, is thus now required to wear safety glasses, something that has been met with frustration. See Table 8 for some representative quotes from the interviewees regarding the social influence and motivation

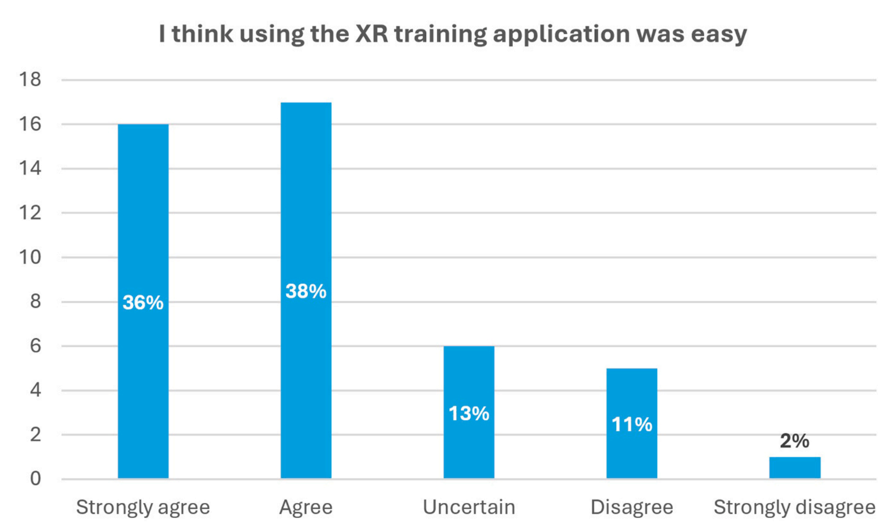

Fig. 14. Survey result of the perceived effort of using the XR training.

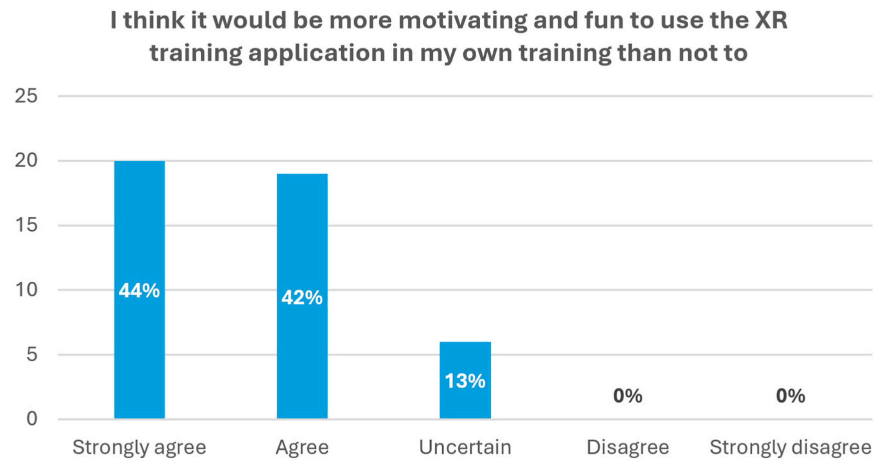

Fig. 15. Survey result of the motivation to use XR training in own training.

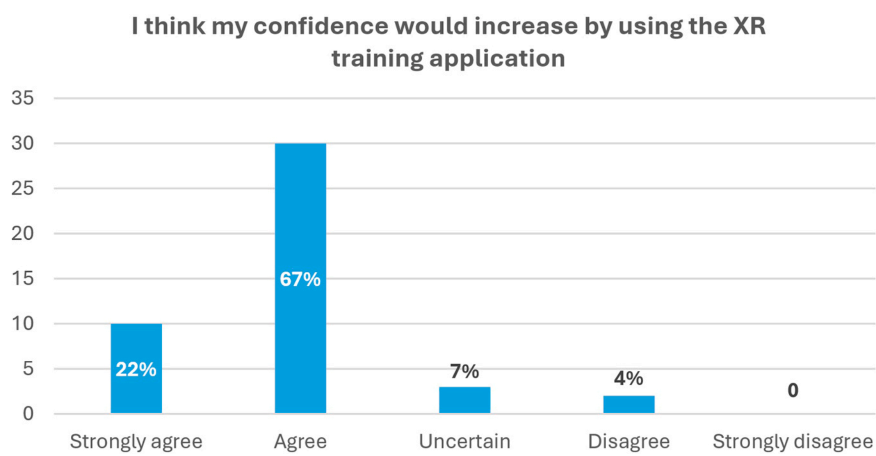

Fig. 16. Survey result of the effect that the XR training could have on the trainees confidence level.

Table 8
Most representative quotes regarding the social influence of using the XR training.

Social influence	*Most representative quote(s)*
Fun / Engagement	**P10:** "*It is always fun to work with new technology*." **P20:** "*This (XR training) is something different which is exciting, the training would probably be less boring.*"
Stress level / Confidence	**P13:** "*This (XR training) doesn't show your mistakes in the same way, and it has no real consequences, so for new people it would be a lot less stress.*" **P34:** "*When you are new you are very stiff and afraid when doing the movements, doing it in XR first would be more relaxed.*" **P39:** "*When I started here, I felt useless, as I messed up a lot in front of my supervisor.*"
Target group	**P3:** "*Older people that have work experience might not like it*". **P32:** "*The new hires here are from a younger generation, and they are used to this technology so they will love it.*"
Risk of injury	**P4:** "*Last week a new guy got sealant material in the eye during the training*" **P15:** "*Today we train with (safety) glasses, because if you don't know what to do sealant can get in the eye. With this (XR training) we would not need that.*"

towards using the XR training.

6. Discussion

The demonstrated XR training in this study presented a solution for technical skills training in manufacturing, including motor-skills. Virtual alignment between the physical tool and the virtually applied sealant in the training application eliminated the need for real sealant material, traditionally used in the training, while maintaining realistic movement patterns, haptic feel and visuals. The use of the physical sealant tool and car body in this study made sure that realistic haptic feedback was achieved throughout the training, which is essential for the development of transferable tactile feel and motor-skills [40]. Moreover, the MR capabilities of the HMD made it possible to track and visualize the tool in real-time to maintain realistic hand-to-eye coordination. As shown by Kaluschke et al. [28], maintaining eye-to-hand (or eye-to-tool) coordination in VR with a proper alignment between the physical tool and the virtual representation of the tool is essential for the transferability of the learning of motor-skills into a physical context.

At the same time, Hsiao et al. [30] have shown that virtual misalignment of up to 70 mm is rarely noticed or perceived by the users as it is in the range of the users' natural sensory biases. It can thus be argued that the 7.7 mm average error margin between the real sealant line and the virtual representation of the sealant line achieved using the developed XR training in this study is accurate enough to maintain sufficient eye-to-hand coordination.

Although sufficient for eye-to-hand coordination and the development technical skills, the tracking error of 7.7 mm is higher than what would be considered within tolerance for the real sealant application in the factory [45]. The visual misalignment caused by the tracking error in the training might introduce issues such as slightly bias in the positioning of the tools during the virtual training resulting in limited fine precision training.

When comparing the measured tracking error in this study with literature on other conventional XR tracking solutions, the results align well with similar conventional systems tested in similar experimental setups. For instance, Pereira et al. [47] measured the tracking accuracy of the Meta Quest 2 controllers between 1,24 – 13,75 mm depending on the speed and translation direction of the manipulator. Schlenker et al. [44] measured the average tracking error of the Magic Leap 2 HMD using the Vuforia tracking solution to 2,4 mm. Similarly, Kuhlmann de Canaviri et al., [55] measured the average tracking error of Steam VR using HTC Vive trackers during dynamic movements of 50 mm/s to 11 mm when using two HTC base stations for tracking. Their study also found that tracking performance drastically increased with decreasing speed of the tracked object and were able to achieve submillimeter tracking accuracy only for static positions.

From the above referenced studies, none would pass the tolerance of the actual sealant bead which could vary in width from 4 to 14 mm at velocity above 100 mm/s [45]. Reliable sub-millimeter tracking during dynamic motions can generally not be achieved by standalone consumer XR systems and would typically require an integration with an external motion capture system [56].

However, for early-stage stage motor skill training, with less precise tolerances outside of real production, conventional XR systems could still be used. This was also emphasized in the user study where a clear majority (71%) of the current sealant operators found that the XR applications could be used in the demonstrated manufacturing use case to facilitate learning of the task. Among these, a majority believed that the learning performance would increase by using the XR training. Improved training performance was attributed to its ability to provide real-time feedback and to increase the number of repetitions in the training by eliminating the need for cleaning and handling the sealant material. Due to their participants experience from working with sealant on a daily basis, their input should be seen as trustworthy and of high relevance to the results of the overall study. The qualitative results from the user study, conducted with subject matter expert participants, confirm that learning of manual sealant skills can take place using the demonstrated XR training and indications towards improved learning compared to traditional training are anticipated. However, no quantitative evaluation of the actual measured increased learning performance was established in this study, and the result is thus limited.

Moreover, some participants highlighted the misalignment of the tracking and a lack of realistic simulating and visualizing the sealant material as a shortcoming and a hindrance for increased learning performance. As can be seen in Fig. 11, the expected learning performance (PE) is thus not seen as the main contributor to the user acceptance of the XR training. The construct of SI scored the highest, indicating that, for instance, the ability to train without consequences of errors in order to increase the confidence level of the trainees, and the engagement and motivation that the participants felt to use the XR training application has a stronger influence over user acceptance and usability in industry.

The UTAUT results of the user study and the construct of EE, also show that XR technology is mature enough to be easily handled and used in an industrial setting by users without previous XR experience. Standalone headsets like the Meta Quest 3 and similar, with technology such as passthrough were highlighted as a strong contributor to the ease of use by the participants and can be seen as significantly lowering the entry barrier for XR adoption and usability in industry [57].

The application of XR training in the particular use case was also seen to contribute to several business motivating factors identified by the automotive case company at the start of the project. For instance, 44% of the participants interviewed during the user study pointed out the benefits of reduced wasted material and the reduced time spent on cleaning and resetting the training as some main benefits. During the interviews it became clear that the vast majority of today's training is spent on cleaning and material handling, which is non-value adding activities for the trainees learning curve. At the same time the case company states that a new sealant operator is spending several weeks training before contributing to the real production. It can thus be argued that a XR training solution that eliminates the need for non-value-adding activities such as material handling and cleaning would save the case company multiple days spent on training per operator. Which will lower the overall changeover time in between product or model year changes and employee turnover.

Moreover, time could be freed up from the trainer or supervisor who no longer needs to assist in the cleaning or assessment of the trainee to the same extent. Overall, this indicates that there could be financial motivation towards the implementation of XR training, besides the support it gives the trainee.

With the purpose of building technical skills, transferable in a real manufacturing context, beyond the cognitive element of learning, the findings of this paper indicate that XR trainings could be used. The advances in spatial computation and the ability to bring in real physical tools and props into virtual training are seen as a key-enabler of the development of technical skills in manufacturing. However, questions remain regarding the fidelity in tracking by the XR systems in order to learn precision movements and accuracy. Until proven otherwise, recommendations are made to use XR training for early technical skills development, building motor-skills and muscle memory of tool handling, while parts of the physical training should remain to teach accuracy and precision. Thus, for high precision tasks, XR training should be seen as a complement and not as a fully replacing the existing training.

Although the user study was carried out on one specific sealant station, the developed XR application could be scaled to multiple sealant tasks, stations and adjacent industries. The feature to recalibrate the TCP position and to record benchmarks for new sealant lines from within the application itself, means that the solution could easily be updated to any product or sealant tool. A trainer, or experienced sealant operator, could potentially record a new benchmark and recalibrate the training to work on any kind of product within minutes without external support. Which could make it more financeable viable also in a low-volume and high-mix production by overcoming threshold of time-consuming and XR costly content creation and development [12].

Furthermore, several characteristics of the task are shared across a broad range of industrial manufacturing processes and domains. These include continuous tool trajectory control, precise TCP positioning, visuomotor coordination, and force control. Consequently, the findings may generalize to other manufacturing domains where operators are performing complex tool handling and where eye-to-hand (*or eye-to-tool*) coordination needs to be trained. With small modifications the system could be updated to replicate a variety of tool handling applications within adjacent manufacturing domains.

For instance, in industrial painting applications, operators must maintain a consistent spray distance, angle, and speed to achieve uniform coating thickness and avoid defects such as overspray or uneven deposition [58]. Similar requirements exist in manual welding processes, where weld quality depends heavily on torch orientation, speed, and path consistency. XR trainings built on, or inspired by, this study, which incorporates physical props and spatial computation in a MR environment for visualizing optimal trajectories and acceptable tool orientations, while providing a virtual overlay of the material application or removal and could be seen as possible [18,58]. Likewise, the findings of this study could also be applied in other critical sectors where motor-skills and eye-to-tool coordination is to be trained. For instance, similar studies using conventional XR systems for eye-to-hand coordination in surgical simulation training exist, showing promising results [59].

The result of this study emphasizes that companies that are currently spending large resources on material and time invested in training technical skills among new operators should explore the use of XR training as a complementary training to a larger extent.

6.1. Limitations & future work

Several limitations and lessons learnt could be considered when interpreting the findings of this study and the developed demonstrator. The integration of real tools and physical props was critical to maintain eye-to-hand coordination for motor-skills training and user acceptance. Based on research from Hsiao et al. [30], the average achieved tracking accuracy with an error margin of 7.7 mm was assumed to be within the range of the users' natural sensory bias, thus enough for eye-to-hand coordination. Meanwhile the user study showed that even small misalignments between virtual and physical elements negatively impacted perceived realism and that the tracking accuracy could be seen insufficient for training on tasks requiring extreme high precision.

Limitations in consumer grade inside-out tracking as used by the Meta Quest 3 exist but more so the granularity of the TCP tracking in the training software together with environmental conditions could have been a contributing factor to the error margin. Moreover, the lack of physical simulation of the liquid sealant material such as the absence of realistic viscosity and bead deformation could limit the possibility to practice on realistic tool and material handling using the developed XR training.

Based on these findings, future iterations of the system should prioritize improved tracking precision, tighter calibration between physical and virtual components, and enhanced real-time physics-based material simulation. Additionally, training designs should consider progressive learning scenarios and better integration into existing industrial training workflows.

Future work should also explore the integration of Artificial Intelligence (AI) to enhance XR-based training systems for technical skills by providing personalized and data-driven experiences. For instance, Machine Learning (ML) could be used to evaluate trainees' motor-skills performance based on motion and interaction data and predict training paths [60]. Meanwhile, Large Language Models (LLMs) could provide real-time, context-aware guidance through conversational interfaces embedded in the XR training [61].

The user study was limited to a single case company and industrial context which may limit the generalizability of the results applicable for other tasks or companies. Furthermore, the user's exposure to the XR training application was limited to a single session of 15 min. Long-term learning effects and retention over multiple training sessions or user fatigue and cybersickness from extended use were thus not captured and measured. As discussed by De Giorgio et al. [22], suitable performance metric in measuring the effects of XR training in comparison to other systems needs to be defined and investigated. Without such metrics and comparison, the absolute truth and best practice will be difficult to conclude. Future work should thus include development of performance metrics for technical skills training and longitudinal user studies to evaluate the effect that XR training has on the long-term learning performance and retention of technical skills.

This study primarily focused on evaluating the technical and operational feasibility of the proposed XR training by measuring its tool tracking accuracy, the user acceptance and usability of the system. Therefore, no comparative study against a baseline training method was conducted to quantify and advantages or disadvantages of the learning outcomes or the training efficiency. The claims of reduced training time, reduced material waste and the possibility to learn using the system are thus remain unquantified as they are derived from the qualitative results of the interview and survey study. Critical future work once the solution is implemented at the training stations of the case company would be to run longitudinal studies to quantify the effect the XR training might have on the performance of the operators and on the training efficiency. Moreover, future work should also expand the study to multiple manufacturing domains and stages with various complexity of motor skills to demonstrate the adaptability of the proposed solution and generalizability of the findings.

Despite high record of usability following the UTAUT model in this study, it was limited by disregarding facilitating conditions (FC), crucial for industrialization. Several key challenges still remain when scaling the solutions across industrial environments. For instance, organizational challenges such as cybersecurity, privacy concerns and IT infrastructure together with onboarding of trainers and increased cognitive complexity is hindering its scaling [32]. Also confirmed by the case company, future efforts in these domains are needed to further scale the industrialization of the XR training in their company by bringing it into their normal training routine. Future work including mapping best practices and enablers for implementation and scaling in an industrial context is thus suggested.

7. Conclusion

This study was set out to evaluate the use of XR technology for technical skills training in manufacturing, using manual sealant application as a use case. By tracking and integrating a physical sealant tool in the XR training application, realistic eye-to-hand coordination and physical feedback were maintained and found essential for motor-skill acquisition. A lab experiment demonstrated an average tracking error of 7.7 mm, passing the threshold of visuo-proprioceptive for eye-to-hand coordination, indicating that consumer grade XR systems could provide sufficient fidelity for supporting eye-to-hand coordination and technical skills development. Meanwhile, the tracking error surpassed the tolerance of sealant applications in running production, making it less suitable use in running production or late-stage training.

The on-site user study, involving 45 professional sealant operators, revealed strong usability and acceptance. Participants emphasized the benefits of increased repetition, reduced cleanup time, reduced waste and improved confidence among new trainees. Although concerns regarding realism, particularly material behavior and positional accuracy, limit the system's ability to fully replace physical training, operators broadly recognized its value as a complementary tool in the early stages of training.

Overall, the findings demonstrate that XR technology can support the development of motor-skills in technical training for manufacturing, when designed to incorporate physical props and spatial alignment for realistic haptic feedback. However, in high precision manufacturing tasks it should be viewed as a complementary training technology to the existing training to minimize accuracy bias caused by limited realism and tracking accuracy.

Future work includes improving tracking precision of the XR training and the integration of realistic real-time material simulation for improved usability. Furthermore, longitudinal studies to empirically measure the learning performance and effect is suggested to solidify and quantify the findings of this study. Lastly, best practices should be established to address operability of XR training in manufacturing industries.

CRediT authorship contribution statement

Björn Johansson: Writing – review & editing, Supervision, Project administration. **Puranjay Mugur:** Writing – review & editing. **Omkar Salunkhe:** Writing – review & editing, Methodology, Investigation. **Dan Li:** Writing – review & editing, Project administration, Methodology. **Henrik Söderlund:** Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT for proofreading, refinement and readability enhancement. The authors reviewed and edited the content as needed and takes full responsibility for the content of the published article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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