Digital Twin-based Instructor Support System for Excavator Training

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Abstract

Given the severity and magnitude of accidents caused by excavators all over the world, the training of excavator operators plays an important role in ensuring the safety of construction operations. New training modes, such as Virtual Reality-based (VR) training simulators, have started to transform training in the construction industry. Although these new developments have been proven to be very effective, it is unanimously agreed by instructors that they do not substitute on-equipment training. During the on-equipment training, an instructor needs to monitor several novice trainees and provide feedback to ensure a safe learning environment. However, being outside the cabin, having to focus on multiple trainees at the same time, and having to stay at a safe distance, instructors are very susceptible to missing important details about the performance of the students. This oversight, in the long term, can result in the institutionalization of wrong behavior in the trainees, which is then very difficult to unlearn. In recent years, with the advent of cyber-physical systems and digital twins, it has become possible to support instructors by providing them with a digital replica of trainees' operations. However, to the best of the authors' knowledge, there has been no systematic research on the use of digital twin as an education/training support tool in excavation training. To this end, this research proposes a comprehensive instructor support system that utilizes a digital twining approach to help instructors circumvent the limitations of traditional training. A prototype is used in a case study to indicate the potential of the proposed approach. It is shown that the proposed system offers great potential in supporting instructors to provide more in-depth feedback to the trainees.

Keywords –

Digital Twin, Excavator, Training, Support System

1 Introduction

Statistics suggest that jobsite injuries and fatal accidents are significantly high in the construction industry [1]. Among others, inadequate knowledge and skills of the workforce account for a large portion of these accidents[2] That is why effective training is especially important in this industry. This is particularly the case for complex heavy equipment such as excavators [3,4] However, the large equipment size, proximity hazards, complex kinematics, high costs, and limited human capital render training or operators especially challenging. To address these challenges, current excavator operator training includes theoretical and practical components, which focus on equipment mechanics, rules, and safety during theoretical sessions [5]. The practical training can be delivered in two forms: (1) simulator training using virtual reality scenes [6], and (2) on-equipment training using actual excavators for hands-on tasks.

While valuable, simulator-based training, where trainees use VR-based devices to experience near-real working conditions, has several limitations. These include limited contextual interaction, potential cybersickness, and insufficient physics simulation [7,8]. Besides, the extensive integration of VR simulators in curricula demands substantial investment and instructor training. This can be a significant adoption barrier [9]. Consequently, VR-based simulators are not commonly perceived as a complete substitution for on-equipment training, which remains preferred for safety instruction [10].

On the other hand, on-equipment training also has limitations pertaining to safety risks and costs [11]. This is because inexperienced trainees may struggle with hazardous situations. Limited access to expensive excavators puts a cap on training time, and budget constraints result in an imbalanced instructor-to-trainee ratio [11]. These limitations impact feedback quality during practical sessions. Addressing these challenges is crucial to optimize the effectiveness of on-equipment training.

Effective practical training heavily relies on instructors providing content-rich, relevant, specific, and timely feedback [12–14]. Lack of feedback during psychomotor skill training can lead to the institutionalization of incorrect behaviour[15]. While instant feedback enhances temporary performance [16], conventional methods have limitations such as disrupting workflow continuity, providing feedback from an outsider's perspective, safety concerns leading to a safe distance, and challenges in assessing multiple trainees simultaneously[17,18]. These issues call for a new feedback approach in excavator training that assures high-frequency, relatable, and non-intrusive feedback. Besides, current excavator training lacks clear skill indicators and it relies on instructors' subjective assessments. While some quantitative indicators exist[19,20], they mainly measure performance rather than skill. Proficiency-based indicators related to smoothness, joint velocity, force distribution, and motion consistency are considered more suitable for skill assessment, but their effectiveness is unclear.

In recent years, sensor-based monitoring of construction equipment has become popular [21,22]. With all these systems in place, it is nowadays possible to accurately capture the fine details of excavator operations using sensory data. On the other hand, an influx of research on construction digital twinning provides a solid base for using sensory data to rebuild the operation in the virtual world [23]. However, the research in the development of a digital twin as a means to support the training process is unprecedented.

This research hypothesizes that an instructor support system that records trainees' performance in a non-intrusive manner can address these issues. In other words, building a digital replica of the training process (i.e., digital twin) can help instructors address many of the existing limitations in their work. This system aims to offer specific, spatiotemporally referenced feedback through a VR environment, allowing instructors and trainees to review performance with clarity and detail. While the previous work of the authors has presented the technical specifications of such a digital-twin-based system [24], a thorough analysis of system requirements from the instructors of view was not presented. Given that the success of such an instructor support system depends heavily on the perfect alignment between system functionalities and instructors' needs, it is important to analyze the user perspective on such a system. This paper outlines the high-level requirements of such a system and presents a case study to indicate its feasibility.

2 Research Methodology

To achieve the research objective, we employed the System Development Lifecycle (SDLC) V-model design methodology proposed by Balaji and Murugaiyan [25]. Initially, user requirements were identified through a two-fold process: (1) a thorough review of pertinent literature from scholarly sources covering topics such as equipment safety, equipment operator training, VR-based training simulators, and equipment tracking and visualization, and (2) conducting intake meetings with system users. These high-level user requirements served as the foundation for the entire system development and later served as assessment criteria at the project's conclusion to evaluate the instructor support system's alignment with these requirements.

The subsequent step involved translating the client's overarching requirements into the functional requirements of the system. This transformation was achieved through stakeholder analysis and multiple meetings with instructors and managers at SOMA College. The goal was to delineate the anticipated functions of the instructor support system and conduct an analysis of feedback types. Understanding commonly provided feedback to trainees and prioritizing different feedback types was crucial for the system's ability to furnish automated cues for POAs.

Following this, the functional requirements guided the creation of a conceptual model, outlining the type and quantity of modules (e.g., motion tracking, head tracking, VR environment) essential to deliver the identified functions.

The subsequent phase involved crafting the technical system architecture. By evaluating various hardware and software alternatives identified in the previous step, the most efficient options for each module were determined. Throughout this process, alternatives were assessed against the high-level system requirements defined by users. For example, a comparison between GPS and Ultra-Wideband considered factors like accuracy, reliability, and cost to ascertain the optimal choice for the system. The outcome was a comprehensive system architecture detailing the structure of the instructor support system.

In the final stage, a prototype was developed and subjected to testing in a case study. User feedback was collected to evaluate the prototype's efficacy in meeting user requirements.

3 Requirement Analysis

3.1 Stakeholder Analysis

Table 1 shows the stakeholders involved in this research, their viewpoints, and their needs. Each view involves specific stakeholders that have certain goals. Based on their goals, several needs can be extracted. Using (INCOSE, 2015) guidelines, these needs can be converted to high-level requirements which can be verified during the system design cycle.

Knowledge institutions, such as universities, are actively engaged in the project from a corporate perspective, aiming to assist the industry in minimizing excavation damages. Their primary objective is to initially identify shortcomings in the current operator training program and subsequently address them by proposing and showcasing innovative technological and organizational solutions.

The initiative introduces a novel approach to training construction equipment operators, which impacts excavation contractors and asset owners, such as road agencies. Accidents on construction sites are undesirable for both contractors and clients as they lead to project delays and financial costs. The majority of these accidents result from a failure to adhere to safety instructions while operating construction equipment. Consequently, contractors look for operators with market-ready skills acquired through an optimal training program. Likewise, project clients prefer to collaborate with contractors who have highly skilled operators.

Table 1 Manuscript margins

Stakeholder	Need
Knowledge Institutions	Helping industry to reduce excavation damages and injuries by identifying the limitations of the current practice and trying to tackle them
Asset Owners	Less damage and safety hazards on the construction site
Training Schools	Use limited resources at their disposal in a more efficient way and train operators with higher sets of skills
Excavation Contractors	Hiring skilled operators who can perform safe and productive excavation operations
Instructors	Use their limited time efficiently to make sure trainees make good progress with their training
Trainee	Use their limited time efficiently to make sure trainees make good progress with their training

The project has a direct impact on instructors and trainees at training schools, who are very important figures in vocational training programs. On-equipment training sessions create an environment for instructors to supervise trainees directly, offer feedback, and observe trainees' skill improvement based on the feedback. Instructors aim to maximize their time during these sessions to provide more valuable feedback to trainees efficiently. Simultaneously, trainees are eager to comprehend this feedback more clearly to acquire the skills essential for their future careers as construction equipment operators as fast as possible.

3.2 Functional Requirements

After conducting the stakeholder analysis outlined earlier, a workshop involving four instructors and two educational support staff was conducted, alongside informal interviews with instructors and training school managers. The goal was to discern the system's functional requirements, a task approached indirectly due to the limited technical insights on the part of interviewees and workshop participants. These interviews were deliberately unstructured and informal, fostering creativity in generating valuable requirements. To guide the discussion, a set of questions was devised and is detailed in Table 2.

Table 2 illustrates that functional requirements were derived from the responses of SOMA instructors and management representatives. According to these requirements, the system should:

1. Capture the movement across all degrees of freedom of construction equipment, as illustrated in Figure 1.
2. Monitor the head pose of trainees, particularly rotation inside the cabin, to track their shoulder-check tendencies.
3. Provide visualization with centimetre-level accuracy (measured at the bucket tip in Figure 1) and a frame rate of at least 60 Hz. Rotation accuracy should be around ±1 degree with a drifting error of no more than ±1 degree/hour. Positioning accuracy (i.e., translation of the excavator in Figure 1) should be 3 meters.
4. Represent the pose (i.e., location and orientation) of other equipment in the vicinity.
5. Supply automated cues/pointers to instructors, indicating POAs for feedback.
6. Offer offline visualization while being fast enough to support feedback within 24 hours.
7. Feature a user-friendly GUI for instructors to interact with the virtualized training site, encompassing 3D navigation and the ability to traverse training sessions in time.
8. Include a feature for instructors to annotate feedback in timestamped text.
9. Incorporate a feature allowing the replay of annotated visualizations for trainees.

An additional desirable functional requirement was also identified: the system should enable trainees to use the same virtual environment to practice operations based on provided feedback using joysticks.

Among the outlined functional requirements, requirement 5 required further clarification. This was necessary because instructors offer a diverse range of feedback to trainees, and for the system to generate automated cues/pointers to POAs, understanding the typology of feedback provided to trainees is crucial. Given the time constraints of the project, implementing automated cues/pointers for all feedback types was not feasible. Consequently, it became essential to establish the priorities of various feedback types, leading to the consideration of only the top 5 types for automated cues/pointers.

Table 2 Functional requirements of the system

Questions	Functional Requirement
What aspects of equipment need to be represented in the visual representation?	The system must capture all degrees of freedom of the excavator. This includes the full motion of the arm, the rotation of the superstructure, the rotation of the tracks, and translation of the excavator, as shown in Figure 2
What aspects of trainees need to be represented in the visual representation?	The system must capture the rotation of the head of the trainee. This is important to make sure trainees perform the shoulder check and blind-spot control when needed during the operation
What level of detail and accuracy of the visual representation of trainees' performance is considered sufficient for providing feedback?	Given that the focus of the accuracy is on the position of the bucket tip with respect to the ground, the system is expected to have an accuracy of about a few centimetres. Additionally, the rotation accuracy should be around ± 1degree with a drifting error of ± 1degree/hour. The positioning accuracy needs to be in the order of 3 meters. The visualization of the performance must also not be lagging This can be translated to requirements for the data capture frequency of at least 60 Hz
What aspects of the context of the operation (i.e., surrounding environment) need to be represented for the feedback?	The system, at this stage, is not expected to track the changes in the terrain (i.e., soil tracking). But, the movements of other equipment need to be captured in the visualization.
During the feedback sessions, what aspects of the trainees' performance are being analyzed?	The system should help analyze certain aspects of the trainee's performance in terms of automated cues/pointers to POAs for the instructors. These aspects are explained in detail in Table 3
When is the feedback to each trainee expected to be delivered?	The system is not required to be real-time. The instructors would want to give feedback to students within 24 hours
How much time do instructors envision to spend on reviewing the feedback of each trainee?	The system should be able to speed up and down the reply of performance visualization. Instructors mentioned that the system should potentially be able to reply to the entire operation of about 1 hour in 5 minutes (approximately fast forward x12)
How would instructors expect to provide feedback?	The system should enable at the very least timestamped textual feedback
How are trainees expected to interact with the feedback system?	The system should enable, at the very least, the reply of annotated visualization (i.e., visualization + timestamped textual feedback) at different playback rates. It might be also beneficial for trainees to be able to switch to interactive mode of the feedback system to practice the operation in the virtual environment in the actual context of the work

To identify and prioritize these feedback types, workshop participants were queried about the typical feedback they usually provide to trainees. To facilitate discussion and guide participants in thinking about feedback types, a set of ten predefined feedback types was presented to instructors, drawing from literature reviews and observations of on-equipment training sessions. Throughout the workshop, instructors also proposed new feedback types they deemed necessary. The suggested feedback types are detailed in Table 3.

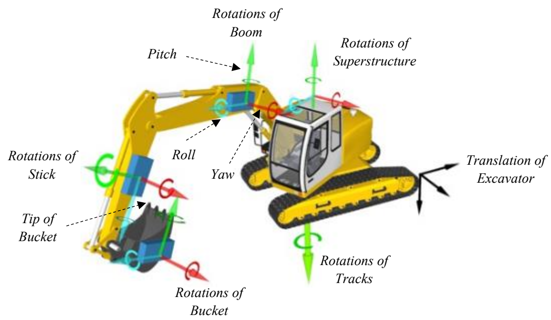

Figure 1. Required degrees of freedom for visualization of an excavator

The instructors who participated in the workshop played a key role in determining the priority of feedback types. They were tasked with assigning a score to each feedback type on a five-point scale, where 1 indicated "Not Useful," 2 represented "Partially Useful," 3 denoted "Useful," 4 signified "Very Useful," and 5 indicated "Crucial." Subsequently, the mean of the scores provided by instructors was computed to establish the ranking of feedback types based on their priorities. The outcomes of this ranking are illustrated in Figure 2.

Considering the project's time constraints and the ranking depicted in Figure 2, six feedback types were chosen for implementation in the instructor support system. From the top 8 feedback types, specifically operator concentration points and excavator vibration, required additional sensors beyond those necessary for capturing the motion of the excavator and trainee. Consequently, it was collectively decided (in consultation with the instructors) to exclude these two feedback types. Consequently, the final set of feedback types supported by automated cues/pointers for instructors' POAs comprises:

1. Shoulder check
2. Bucket movement smoothness
3. Bucket loading distance
4. Simultaneous axes movement
5. Axes movement speed

Additionally, an extra type, stability check, was later introduced during the project by experts. Since this feedback type wasn't part of the workshop discussion, it is treated as an additional aspect.

Table 3 Functional requirements of the system

Feedback Type	Description
Shoulder check	This feedback type targets situational awareness of operators by detecting the gaze point of the operators while they are moving the excavator backward. In this situation, the operators should look back in that direction of movement otherwise the maneuver would be unsafe
Operator concertation point	This metric also targets the situational awareness skill of equipment operators. While performing a swing action on the excavator, the operator should focus on the bucket destination rather than following the bucket position itself
Scenario evaluation	Each trainee is responsible for practicing specific tasks (e.g. dumping a truck) in a collaborative training scenario with other trainees. This feedback type concerns how well the trainee performed the assigned task
Simultaneous axes movement	An efficient maneuver from the equipment fuel consumption perspective is defined as moving the joints of the excavator at the same time as much as possible. This feedback type indicates that the operator is moving the joints simultaneously or not
Bucket movement smoothness	The excavation performance of operators depends on how smooth they move the bucket. This feedback type concerns the movement smoothness
Bucket load	This feedback type focuses on the number of soil operators load during each maneuver. If this amount exceeds from a certain threshold which depends on the excavator specifications, the maneuver is not efficient
Trench geometry	The geometry of the trench dug by operators is an important indicator of excavator performance. This feedback type evaluates the trainees' performance based on geometrical parameters of the trench, e.g., trench depth
Operator drowsiness level	This metric determines the drowsiness level of operators while they are working with the excavator
Operator stress level	This feedback type addresses the stress level of trainees while working with the excavator
Axes movement speed	This feedback deals with how fast operators move the excavator arm in each manoeuvre
Excavator vibration	This feedback concentrates on the extent of vibration induced to the excavator tracks during the operation. If trainees are not experienced enough, lots of vibrations are generated over the excavator tracks
Bucket loading distance	This feedback concerns the amount of pressure on the hydraulic jacks while trainees dig. When trainees lift the loaded bucket, if the bucket is too far or close to the tracks, more fuel is consumed. Appendix 1 provides more detail about this feedback

4 Architecture of the Proposed System

Figure 3 shows an overview of the proposed instructor support system. This figure also illustrates the hardware and software components required to deliver these functions. The initial module of the system, as depicted in the figure, focuses on collecting motion data for the excavator and trainees, including translation, rotation, and head rotation. Tracking technologies are utilized to capture excavator location, pose, and trainee head pose. The module runs in real time. Module 2 integrates, time-stamps, and synchronizes the collected data, necessitating a processor and storage means (e.g., cloud space or local drive). These steps are also performed in real time. Module 3 visualizes stored data in a virtual environment post-training session. This requires a platform for visualization, linking collected data to 3D models of equipment and trainees. In the subsequent module, the system analyzes trainee performance, automatically detecting POAs and providing cues to instructors. Algorithms for POA identification are integrated into an analyzer module within the visualizer.

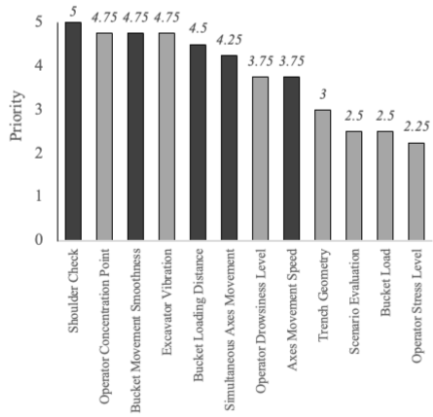

Figure 2. The feedback type priority

In the subsequent module, the instructor assesses trainee performances offline, identifying areas for improvement based on provided POAs and personal visual reviews. A custom GUI facilitates navigation and performance review from various points of view. The instructor can add notes, exporting the annotated virtual scene for trainees. Trainees then receive these annotated VR scenes, gaining insights for future sessions.

In the system's final module, the visualizer transitions to interactive mode, allowing trainees to use control units (e.g., joysticks) for task practice in the virtual environment. This module aligns with functional requirem

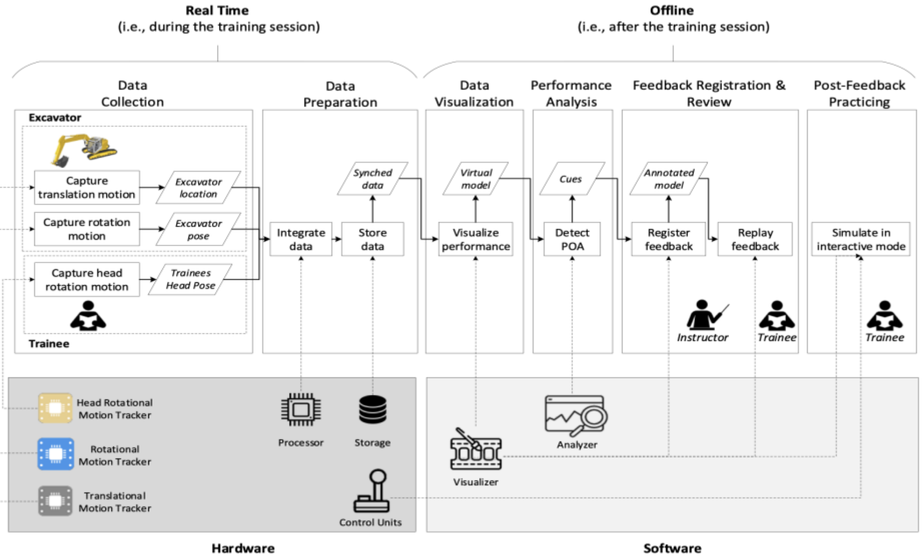

Figure 3. The architecture of the instructor support system [24]

5 Architecture of the Proposed System

The design outlined in Section 4 has been translated into a prototype system. The objective of this prototype is to showcase the viability of the proposed design and evaluate its suitability for the intended purpose. It is crucial to note that the prototype is not intended to function as a fully operational system. This chapter provides a concise overview of the prototype.

5.1 Hardware Components

Figure 4 provides a summary of the prototype's hardware components.

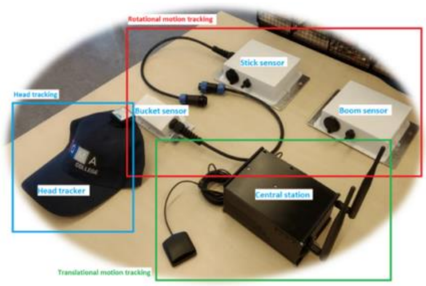

Figure 4. The hardware components of the Motion Capture Module

The system hardware includes 4 IMU sensors, a GPS antenna, and a single-board computer. A cap is employed to monitor the head movement of trainees within the cabin. The connection between the IMUs of the bucket and stick is wired, eliminating the need for WiFi transmission of bucket IMU data and, consequently, the need for a Raspberry Pi in the bucket IMU. As a result, the casing of the bucket sensor is smaller compared to the other two, which rely on Raspberry Pi for WiFi data transmission. Figure 5 shows the configuration of sensors when installed on an excavator. Unity Game Engine [26] is used as a platform for data visualization, performance analysis, feedback registration and review, and post-feedback practice. An interface is designed inside Unity as shown in Figure 6. Figure 6 also shows the main interface of the system for visualization playback and feedback registration.

5.2 Implementation and Case Study

To validate the efficiency of the proposed system, a case study was conducted at SOMA College, i.e., the largest construction equipment training institution in the Netherlands, using the prototype. In this study, an excavator was outfitted with the implemented data collection module, and the trainee's performance was captured on a USB stick. The task assigned to the trainee involved excavating a trench approximately 70 cm deep within 20 minutes. After the experiment, a quantitative assessment via a workshop involving instructors and students was used to assess the system. The assessment form includes a total of 7 general metrics (1 to 7) applicable to both instructors and trainees. Additionally, instructors are evaluated based on 3 specific metrics (8 to 10), while trainees are assessed using 3 distinct metrics (11 to 13). The outcomes of this workshop are depicted in Figure 7.

Figure 7 presents the results of the assessment. Both from the perspective of instructors and trainees, the User Interaction and Real-video Superimposition features received the highest ratings. The 3D navigation feature allows both instructors and trainees to observe and assess performance from various angles. Participants particularly valued the Real-video Superimposition feature for reducing miscommunication by displaying real video alongside the visualization. Moreover, instructors found the Feedback Insertion feature to be an effective means of providing textual feedback. The lowest rating during the evaluation was assigned to Versatility. Trainees expressed comfort with wearing the head tracker during operations and agreed with instructors on the helpfulness of text feedback for performance improvement. However, they noted that the simulator mode did not offer significant added value compared to their existing simulator training program.

Figure 5. The configuration of the system's hardware on an excavator

Figure 6. The interface of the prototype system (adapted from [24])

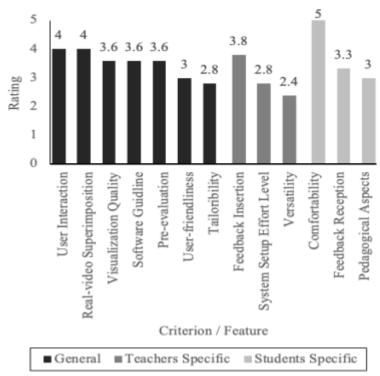

Figure 7. The interface of the prototype system

6 Conclusions

The instructor support system is a cost-effective sensing kit designed to monitor the movements of both the equipment and the operator, offering an interactive interface for educational use. This system empowers instructors to closely monitor trainee performance during on-equipment training sessions from diverse viewpoints, minimizing the likelihood of overlooking cues indicating mistakes. Additionally, it allows trainees to thoroughly review their performance post-training session, ensuring they don't forget instructors' feedback and can maintain focus without interruptions.

Participating experts in the case study affirm that the instructor support system introduces three notable advantages to the existing education system: (1) It effectively addresses the issue of "transience" in the current feedback approach; (2) The system's automatic pre-evaluation feature proves highly valuable, saving instructors time during trainee assessments; and (3) The head tracker provides insights into the trainees' situational awareness.

However, the experts also identify three main drawbacks of the instructor support system: (1) The current state lacks sufficient accuracy in visualization to analyze the quality of trainee performance; (2) The system is currently tailored for a single type of excavator and requires calibration for use with other types; and (3) Integration of real-video recordings with the system is not yet realized, making synchronization with visualization challenging.

There are two points that can be considered in the future. First, in its current form, the system operates as an open-loop system with a unidirectional flow of feedback. The authors have already implemented a simulation mode in the system, where the trainees can practice their improved operation in the VR and send it back to the trainees for re-evaluation. However, this feature is not systematically checked for its usefulness. This will be done in the future. Another direction to pursue in the future pertains to capturing the operation of equipment by tracking the movement of the control units inside the cabin. This tracking allows instructors to better understand the root causes of bad operational habits of the trainees.

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