Design of a **F**eedback **S**upport **S**ystem for the Training of Construction Equipment Operators

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Definitions

Arm   Combination of the excavator boom, its stick, and its bucket

Analyzer   Algorithm that automatically evaluates a trainee's performance

Instructor   Person that instructs the trainee during an educational program

On-equipment training   Practical training program with a real construction equipment

Performance   Motion data of an excavator during an on-equipment training session

Point of Attention (POA)   Digital indicator in a software generated by the analyzer

Trainee   Person that learns to operate a construction equipment

Text feedback   Digital text that provides comments on a trainee's performance

Visualization   Digital reconstruction of an on-equipment training using a software

Acronyms

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CSV	Comma Separated Value
GPS	Global Positioning System
GUI	Graphical User Interface
IMU	Inertial Measurement Unit
LiDAR	Light Detection and Ranging
MBO	Middelbaar Beroepsonderwijs
POV	Point of View
USB	Universal Serial Bus

Preface

This project is entitled "Design of a Feedback Support System for the Training of Construction Equipment Operators" and is sponsored by the SOMA College in collaboration with the Construction Management and Engineering department of the University of Twente. The SOMA College is a vocational school that trains construction equipment operators at MBO level 2, 3 or 4.

In the past two years, I worked on an academic, design-oriented P.D.Eng program that combines research and development. The experience I had during the P.D.Eng. program was different from the experience I had before in the industry. During the program, besides of being a researcher and a developer, I was also responsible as a project manager. The technical challenges in this project were familiar to me, because I had faced almost similar challenges in the virtual reality development projects I have done before. However, the project was really challenging for me from the project management perspective. Specifically, because of the many stakeholders involved in the project (e.g., instructors at SOMA, the Education Coordinator at SOMA, University of Twente, etc.). These stakeholders had varying attitude and interest in the project which made it difficult for me to control the design cycle flow of this project. I will address the project and its challenges in this document based on the following structure.

The introduction which covers theoretical background, problem statement, the project objectives, and user requirement analysis is presented in Chapter 1. Chapter 2 illustrates design methodology for a treatment design. Chapter 3 contains the stakeholder analysis, and functional requirement analysis. Chapter 4 includes the conceptual design. Chapter 5 discusses about the solution space investigation, and the system architecture. The solution implementation from the hardware and the software perspectives is presented in Chapter 6. The results of the system verification and validation are explained in Chapter 7. The solution comparison and its impact are presented in Chapter 9. The Chapter 10 is about the project conclusion. Finally, future work of the project is discussed in Chapter 11.

Graphical Summary
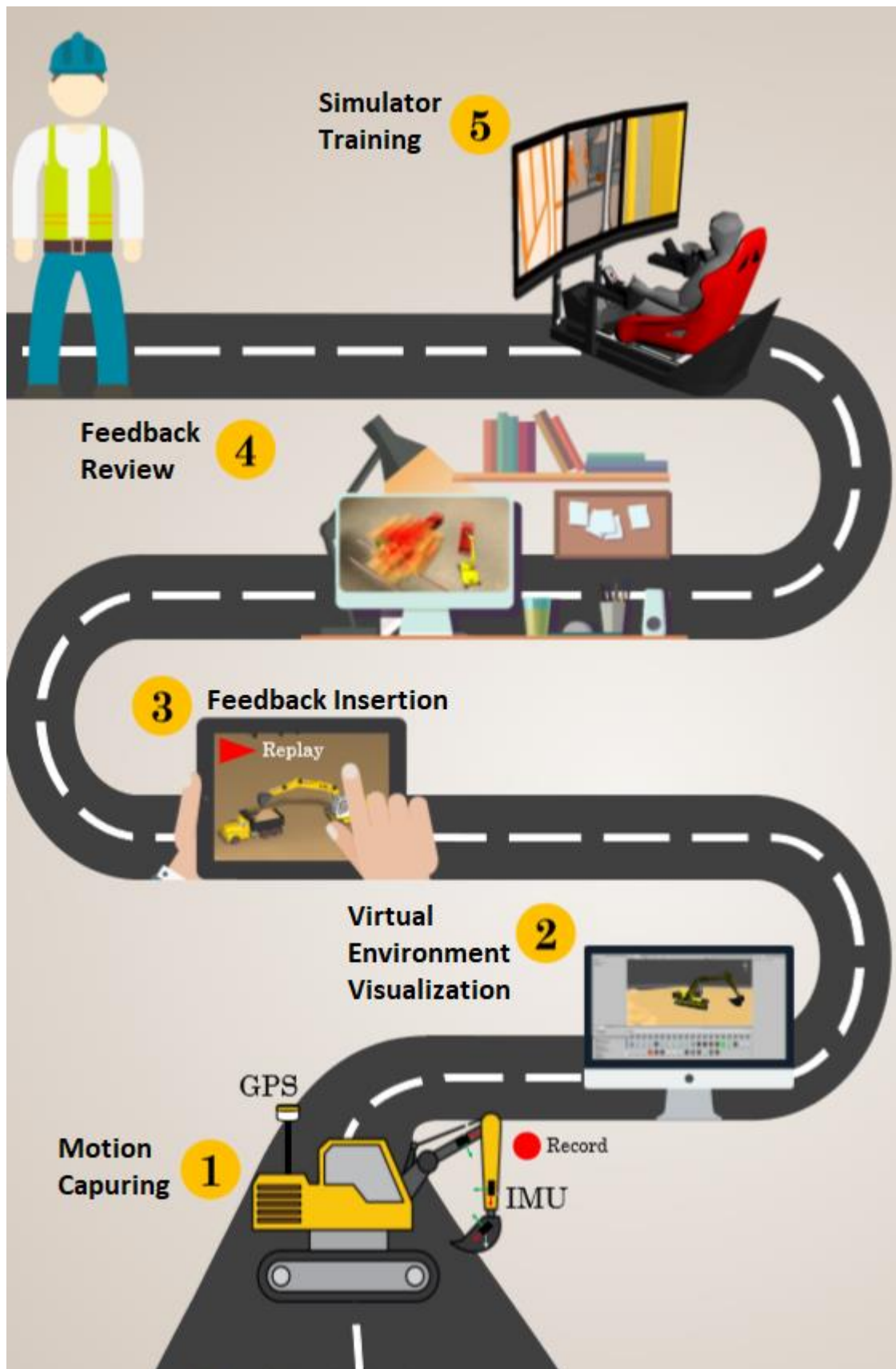
Executive Summary

Feedback Support Systems provide a new means to view and evaluate the performance of construction equipment operators in a virtual environment. The common practice of training operators of construction equipment is through on-equipment training sessions in which instructors directly provide feedback to trainees while they exercise on actual equipment. This way of providing feedback is not optimum, because trainees may forget the feedback after the training session, and instructors may overlook mistakes while focusing on multiple trainees at once. SOMA College in the Netherlands is a vocational school for training the operators for construction equipment and deals with these issues. In collaboration with SOMA College and the University of Twente, a new Feedback Support System prototype is developed to overcome these.

SOMA College required a system, comprising both hardware (i.e., sensing kit) and software, that help instructors to (1) better monitor the performances of the trainees, and (2) provide them with substantive feedback. This system should meet the following high-level requirements:

- **Useful:** the system should identify the needs of instructors and trainees and try to provide them with content that can help the processes of (1) providing (by instructors), and (2) receiving (by trainees) feedback;
- **Accurate:** the system should capture the performance of the trainees with high accuracy;
- **Reliable:** the system should be able to function continuously and consistently;
- **Robust:** the system should be weather-proof;
- **Affordable:** the system should have an economic edge compared to existing solutions for equipment motion tracking;
- **User-friendly:** the Graphical User Interface (GUI) should provide an easy-to-comprehend and navigable platform for instructors and trainees to operate with the system.

To this end, a system is developed that provide the following essential functions:

1. Capture the motion of all degrees of freedom of a construction equipment;
2. Track the head pose of the trainees (mainly the rotation) inside the cabin to track their shoulder check tendency;
3. Offer visualization with the accuracy of 2 centimeters (measured in terms of the position of the bucket) and frame rate of at least 60 Hz. Also, the rotation accuracy must be around 1° with the drifting error of no more than 1°/hour. The positioning accuracy (i.e., translation of excavator) should be 3 meters.
4. Can represent the pose (i.e., location and orientation) of other equipment in the vicinity;
5. Provide automated cues to instructors to signify the Points of Attention (POAs) for feedback. five feedback types were selected through a systematic ranking of possible feedback types by SOMA instructors. These feedback types are:

   a) *Shoulder check;*
   b) *Bucket movement smoothness;*
   c) *Bucket loading distance;*
   d) *Simultaneous axes movement;*
   e) *Stability check*

6. Offer off-line visualization but be fast enough to support feedback;
7. Have a user-friendly GUI for the instructor to interact with the virtualized training site (3D navigation and the training session time travel);

8. Provide a feature for the instructors to annotate their feedback in terms of timestamped text.
9. Provide a feature for the replay of annotated visualization for trainees.

Also, as a supplement to the above functions, the system also provides an interactive mode where trainees can practice and improve their skills based on the provided feedback in the same virtual environment (i.e., post-feedback practice).

The structure of this report which is based on the design stages during the solution development is presented in Table 1.

Table 1. Report structure according to design stages

Design Stage	Description	Chapter
Problem Investigation	- Problem statement definition - Project objectives - User needs identification	Chapter 1
	- Methodology design	Chapter 2
	- Stakeholder analysis - Functional requirement analysis	Chapter 3
Treatment Design	- Conceptual design	Chapter 4
	- Solution space investigation - Architecture design	Chapter 5
	- Solution implementation	Chapter 6
Treatment Validation	- System module verification - Solution validation	Chapter 7

The working principles of the system are as follows: the sensor kit captures trainees performance (in terms of motion data) and save the data to a memory stick. The data is then manually transferred to a local computer where instructors run a software application that visualize the data in an navigable 3D virtual scene. The software application, then, detects POAs and present them to the instructors as cues for feedback. The instructors review the performance of the trainees and annotate the scene with the relevant feedback using embedded and time-stamped notes. The annotated scene is then sent to trainees who can review the feedback. Ultimately, the trainees can switch from navigation/review mode to interactive mode and use joysticks to practice with the virtual equipment in the same context as the actual on-equipment training.

It is discovered that the Feedback Support System can be considered as an affordable sensing kit that tracks both the equipment and the operator motions and provides an interactive interface for educational purposes. The system enables the instructors to closely observe the trainee performance of on-equipment training sessions from different perspectives with a lower chance of overlooking the cues that signal trainee's mistakes. The system also enables the trainees to review their performance after the training session in a more comprehensive way, without forgetting instructors' feedback or losing focus due to interruptions. The system can improve the training of construction equipment operators which finally leads to more efficient and safer excavations in construction sites.

Product Summary

The product summary of the Feedback Support System is a comprehensive summary based on the four criteria for evaluating a P.D.Eng. design project, namely, functionality, construction, realisability, and impact. In following, the P.D.Eng. trainee evaluates the system according to the several sub-criteria in these four domains specifically.

1. **Functionality**

a) *Satisfaction:* SOMA College required (1) a hardware 'sensing kit' that captures the motions of construction equipment and the trainee inside the equipment, (2) translates these motion data into a 3D virtual environment, (3) detects important possible mistakes of trainees, (4) allows instructors to provide visual feedback to trainees, and (5) helps the students to comprehend comments on their performance based instructors' feedback. According to SOMA College statement, the system satisfied the objectives which are mentioned above.

b) *Ease of use:* The system hardware is plug-and-play (but not hot-plug) which can be easily installed on a construction equipment. The transfer of the captured motion data (synched data) to the system graphical interface should be manually done, but by proving Wi-Fi coverage in training sites, the data can be transferred automatically too. During the P.D.Eng. project, a tutorial session was held at SOMA College to guide instructors how to use the system (e.g., installation, performance reviewing, etc.).

c) *Reusability:* The system is developed and tested for excavators, as these provide an example of construction equipment with a complex geometry. Developing a successful system for this complex equipment, renders it possible to – later – also expand the application of sensing kits to simpler equipment with fewer degrees of freedom.

2. **Construction**

a) *Structuring:* The hardware architecture of the system is inspired by Internet of Things that use network technologies to integrate and analyze data coming from a distributed sensor network that interconnect different objects. Its protocols provide a loose coupling between the different hardware components to facilitate extensibility. The software is designed based on an object-oriented programming paradigm to bring high cohesion within the software modules.

b) *Inventivity:* It can be argued that the developed Feedback Support System is the first of its kind to fully support the feedback process of heavy construction equipment using virtual reality and sensor technology. The provided environment allows instructors to give feedback to the trainees, and allows trainees to watch this feedback at their own pace. Another novelty it the tracking of excavator operators attention points. There are manufacturers, such as Topcon, that produce functionally comparable sensing kits for motion capturing. However, these kits are not used to date for supporting the provision of feedback to the trainees. This is because (1) the existing highly proprietary systems provide very limited access to their sensory data and therefore cannot be easily integrated with software applications that support the feedback process; (2) the existing systems focus primarily on the equipment motion and, in doing so, fail to track the performance of trainees (especially head movements) inside the cabin. This combined with inherent lack of support for hardware extensibility in the proprietary systems, makes it difficult to use these systems for capturing the full scope of data needed to provide substantial feedback to trainees.

c) *Convincingness:* The concept of Feedback Support System is empirically tested by a developing a prototype. Several workshops have been held with the instructors and the trainees at SOMA College to (1) identify the user requirements, (2) refine the development, and (3) validate the final prototype. The system was tested with respect to all the high-level requirements (i.e., usefulness, accuracy, reliability, robustness, affordability, and user-friendliness).

3. Realisability

a) *Technical realisability:* The reliability and robustness of the system were tested during two separated test setups which both of them were successful. However, a few steps are needed to make the current prototype ready to use as an integration to SOMA College on-equipment training programs. These steps are (1) replacement of the current IMU sensors with industrial-grade IMU sensors to achieve shock resistance, (2) replacement of the single-board computer with an industrial embedded system to tolerate extreme weather temperature and dust, (3) design a precise calibration process for IMU sensors to improve visualization accuracy, and (4) integrate a video camera with the system to record trainees' performance which can be superimposed to the visualization for better a better performance evaluation.

b) *Economical realisability:* Affordability is one of the high-level requirement of SOMA College for developing this system. Due to that, a cost estimation is performed to assess the affordability of system. Based on the cost estimation, the Feedback Support System is about 20 times cheaper than the available systems in the market for capturing the motion of a construction equipment. Therefore, SOMA College can easily invest on this prototype to make it ready to use and hire it on several machines.

4. Impact

a) *Social impact:* Development of the Feedback Support System had practical impacts on the education system at SOMA College. The process of developing the system contributed to learning between instructors and trainees. The workshops during this P.D.Eng. project provided the opportunity for instructors to discuss the criteria they used for evaluating trainees. To the best of the P.D.Eng. trainee's knowledge, such discussions were not very common in the regular work practice at SOMA. The discussions helped understand the logic behind each criterion and they tried to enhance their strategies for evaluation based on these logics. The workshops made knowledge more explicit and helped understand why instructors evaluate trainees' performance with certain strategies. During these workshops, trainees also understood how instructors evaluate them. The common understanding between instructors and trainees is totally beneficial for trainees because it helps them to acquire motor skills quickly and with better quality. Ultimately, trainees with these skills after graduation can improve safety while working as construction equipment operators in construction sites.

b) *Risks:* The risks in this project can be categorized into three types, namely, (1) resource risk, (2) performance risk, and (3) strategic risk. The resource risk covers time, cost, and external dependencies (e.g., availability of an excavator for testing, or reliability of supply chains for delivering required components during the project development). For time management, the P.D.Eng. trainee tried to clarify the scope of the project in each step by having meetings with his supervisors and the client. For cost management, the P.D.Eng. trainee tried to adapt his design based on available resources at UT and SOMA College (e.g. IMU sensors, GPS sensor, etc.). To reduce dependencies on external factors, field tests were arranged two weeks in advance to ensure the availability of the equipment for testing. For performance risk management, after each development phase the system was presented to the client to receive feedback for improving the system in the next design cycle. Technical strategic risks were easily handled during this project, because in each design cycle, the system was tested in a software test bench before testing on a real equipment. So, many strategic faults would be detected in early stages of the project development.

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1   Introduction

1.1   Background

In the Netherlands, every year an average of 115 workers get injured on construction sites (Ministerie van Volksgezondheid, 2015; Wilkins, 2011). About 42% of the incidents on construction sites are because of insufficient knowledge and skills of practitioners and operators (Haslam et al., 2005). Effective training of construction equipment operators is essential for improving the operators' performance and consequently reducing the number of construction incidents. But, given the sheer size of construction equipment and the hazard of working in their proximity, the complexity of their kinematics and control, the cost of using the equipment, and the limitation in human capital, it is challenging to design and offer an effective training program.

The current equipment training in construction normally consists of two components, namely theoretical and practical training. For theoretical training, trainees are provided with a theoretical background about the equipment mechanics, operational rules/regulations, and safety of operating equipment. The practical training is mainly geared towards preparing trainees to acquire motor skills and dexterity to operate construction equipment. Practical training is offered in two, normally complementary, forms, namely (1) on-equipment training in which trainees use actual construction equipment to perform different tasks. For this type of training, it is tried to expose trainees to near-real working conditions at training sites, and (2) simulator training, in which trainees use training simulators to operate virtual equipment in realistic virtual reality scenes (Oliveira, Cao, Hermida, & Rodríguez, 2007). These sessions are supervised by an instructor and normally held in a classroom.

While proven useful, simulator-based training has a number of limitations that hinder a widespread application (Burke et al., 2006). First and foremost, simulators offer low interaction with the actual context of work to trainees (Sacks, Perlman, & Barak, 2013). Other limitations include cybersickness and limited physics simulation (e.g. soil model) (De Winter, Van Leeuwen, & Happee, 2012). Consequently, it is argued that VR-based training simulators cannot yet be considered as a replacement for on-equipment training (Psotka, 1995). Wilkins (2011) suggested that practical training in a workplace is more influential than classroom training to teach safety (regulation).

The on-equipment training has, therefore, become a mainstream practice in recent years. However, it is an unsafe and costly method. It is less safe because the training with actual equipment creates potentially hazardous situations that an inexperienced trainee may not be able to deal with. This would require instructors to maintain a safe distance to equipment at all times. This results in an increased chance of missing important nuances in the performances trainees. The training is also costly, because, on one hand, the construction equipment is expensive to purchase or rent and, therefore, training schools often operate on insufficient number of equipment. This, in turn, means that there is a limitation on the duration of on-equipment training that can be offered to each trainee. On the other hand, training schools usually face budgetary constraints on hiring qualified instructors, resulting in a disproportionate instructor to trainee ratio. This makes it essential for training schools to ensure that trainees can get the best out of the limited time available during the on-equipment training. Consequently, the quality of feedback provided to trainees become a paramount factor for offering successful on-equipment training.

1.2   Problem Statement

The quality of on-equipment training, to a great extent, is predicated on the content-rich, relevant, specific, and timely feedback provided by the instructors. However, in the current situation, the fashion in which feedback is provided to trainees is not optimal because of the following reasons:

- **Continuity**: Instant feedback from the instructor during the program can disturb the trainee's concentration on the performed task, disturbing the continuity of the workflow.
- **Transience**: By providing feedback to the trainees after the program, it would be difficult for them to recall their sequence of performance.
- **Perspective**: The instructor provides feedback from the outsider perspective (view from outside to the equipment). On the other hand, the trainee is operating from an insider perspective (view from inside the equipment's cabin). The difference between the perspectives may cause some misinterpretations to both of them, as they do not have a common reference.
- **Proximity**: Because of safety issues, the instructor should maintain a safe distance from the equipment. This situation may prevent him/her to observe the details of the trainee performance.
- **Attention focus**: During the on-equipment training program, the trainee should focus on several trainees at the same time. While supervising a trainee, the instructor may overlook other trainees (as visualized in Figure 1).

Figure 1. The instructor is giving feedback to trainee #1 while he does not have the time to simultaneously observe trainee #2 during his on-equipment training

One way to address these issues is to envision a feedback support system that can record the performance of the trainees in a non-intrusive manner and allow instructors to provide specific and spatiotemporally referenced[1] feedback on the visual log of trainees performance offline. Using this support system, instructors and trainees can base their feedback and discussions on unambiguous, accessible, navigable and reusable visual references. This system can help evaluate the training sessions in greater detail and potentially with higher effectiveness since it can provide contextualized feedback that trainees can use after the sessions. However, to the best of the author's knowledge, such a feedback support system for construction equipment does not exist.

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[1] Spatiotemporally referenced feedback means the feedback that is associated with a specific portion of the performance indicating the time, duration, location, involved parts of equipment, and the specific decision made by the trainee.

1.3 Project Objectives

On the premise of the above problem, this project aims to develop a feedback support system for an on-equipment construction training program that can support instructors in providing feedback to the trainees. This system needs to be able to (1) reconstruct the training session in an navigable virtual environment, (2) allow instructors to interact with the reconstructed scene to give feedback, (3) provide instructors with some cues to parts of the trainees' performance that require attention, and (4) allow trainees to review the provided feedback and visually associate the provided feedback with the pertinent portion of their performance.

This objective can be decomposed into the following sub-objectives:

1. Design and implement a sensing kit that captures the important aspects of the training session (i.e., motions of construction equipment and head movements of operators inside the cabin);
2. Translate the captured sensory data into a virtual scene that visualizes the trainees' performance in a navigable environment;
3. Develop methods to detect Points of Attention (POA), i.e., sub-optimal performances or mistakes of trainees during the training;
4. Design a Graphical User Interface (GUI) that provides an user-friendly medium for instructors and trainees to interact with the system;
5. Design a GUI that can help trainees comprehend the improvement they need to make based on the instructor's feedback.

This should be highlighted that, in this study, the Feedback Support System is specially designed for excavators, but it can be retrofitted for other types of equipment in the future.

1.4 Project Client and Client Needs

SOMA College is a vocational school that trains construction equipment operators at MBO levels 2, 3 or 4. They employ a mix of theoretical in-class education, on-equipment training and simulator-based training. Having been dealing with the issue of being understaffed with regards to instructors, SOMA College has been largely investing in the development of simulation-based training. In the course of the past few years, SOMA College managed to developed an advanced simulator classroom which boosts 18 training simulators. They have managed to integrate simulator-based training as an active component of their curriculum. Students use training simulators in the first year of their education at SOMA College. The duration of simulator training is about 100 hours in which students learn how to operate excavators, wheel loaders, graders, and forklifts. The extent and fashion simulators are being used parallel to theoretical and on-equipment sessions, renders SOMA College at the forefront of innovation in construction education both at the national and international scale.

Although simulator training is being used to complement the on-equipment training, similar to other training schools and because of the issues mentioned in Section 1.1, SOMA College still perceives on-equipment training as an integral part of their curriculum. Nevertheless, they experience similar issues to those mentioned in Section 1.2 with their feedback strategy. Therefore, the college has decided to sponsor this project to improve its on-equipment training by means of a feedback support system.

This project intends to develop a support system that can assist instructors in providing feedback to trainees. This will be done by first recording the entire performance of trainees and then visualizing it in a VR scene to allow instructors to navigate through the entire performance from different angles of view (from both inside and outside of the cabin) and give feedback to trainees. In this way, instructors

would be able to review trainees' performances in full, i.e., without overlooking any important nuances due to division of their attention between several trainees, and provide spatiotemporally referenced feedback. Accordingly, the system should be easy to use for the instructors and it must contain all the essential information that they need for the evaluation. An example of this is the excavator bucket trace. The system should also generate a report that visualizes both the trainees' performance and instructors' feedback. This report has to support trainees in understanding the provided feedback. Therefore, ultimately, the system should provide trainees with higher quality training that gives them refined skills for operating in a real construction site.

They expect Feedback Support System to meet the following high-level requirements:

- **Useful:** the system should identify the needs of instructors and trainees and try to provide them with the content that can help the processes of (1) providing (by instructors), and (2) receiving (by trainees) feedback;
- **Accurate:** the system should capture and visualize the performance of the trainees with high accuracy;
- **Reliable:** the system should be able to function consistently under different conditions and for training sessions that may take up to 4 hours at a time;
- **Robust:** the system should be weather-proof and shock-resistant to work in a harsh environment;
- **Affordable:** the system should have an economic edge over the existing solutions for equipment motion tracking;
- **User-friendly:** the GUI should provide an easy-to-comprehend and navigable medium for instructors and trainees to operate with the system.

1.5   Structure of the Report

The remainder of this report is structured as follows. Chapter 2 presents the design methodology that is adopted to pursue the objective of this design assignment, i.e., developing the feedback support system. Chapter 3 discusses the functional requirements of the system. This is developed based on the analysis of stakeholders and workshop with the clients of the project. Chapter 4 presents the conceptual model of the proposed system and discusses several design alternatives that have been considered in this assignment. Chapter 5 presents the final architecture of the developed system in detail. Chapter 6 reports on the implementation of the system. Building on the implementation, Chapter 7 presents the validation of the prototype system, which has been done together with instructors and trainees at SOMA college. Finally, Chapter 9 presents the conclusions, recommendations, limitations, reflection on the design process and future work.

2   Design Methodology

To pursue the objective of this design assignment, a design methodology was adopted based on System Development Lifecycle (SDLC) V-model (Balaji & Murugaiyan, 2012). Figure 2 presents an overview of the adopted design methodology.
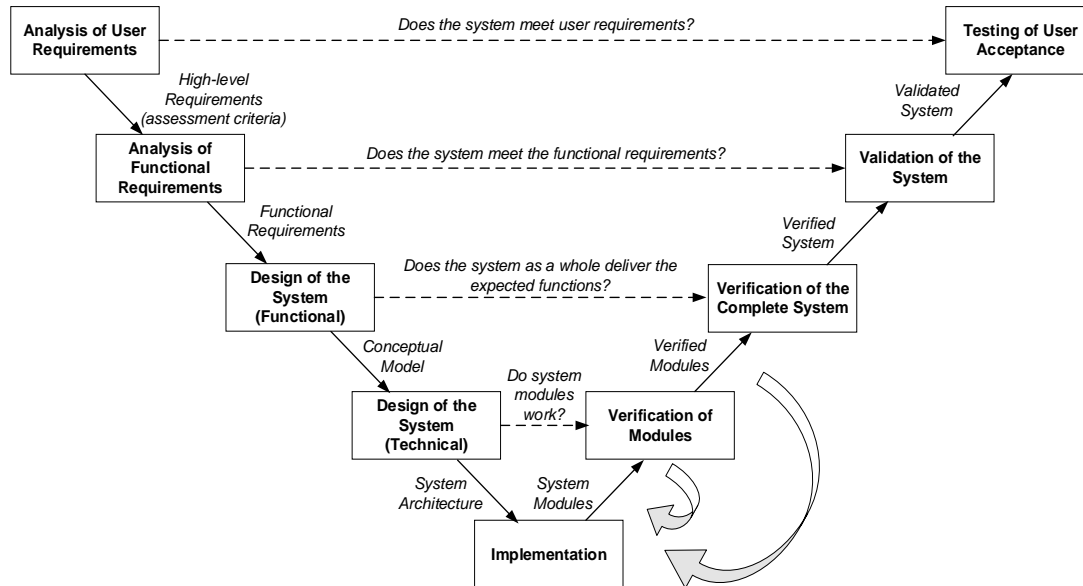
Figure 2. Design methodology for Feedback Support System

As shown in this figure, the first step of the design was to identify the user requirements based on the analysis of the problem. This was done by (1) reviewing relevant literature from scholarly sources (on topics of equipment safety, equipment operator training, VR-based training simulators, and equipment tracking and visualization) and (2) having intake meetings with the client of the system, i.e., SOMA College. These high-level user requirements were used to guide the development of the entire system and also served as the assessment criteria at the end of the project to determine the extent to which the feedback support system is able to meet the requirements of SOMA College. The results of this step are already presented in Chapter 1 of this report to justify the problem and the client's needs and expectations.

In Phase 2, the client's high-level requirements were converted to functional requirements of the system. This is done through performing stakeholder analysis and having several meetings with instructors and managers from SOMA College. The purpose of this phase was to determine the different functions that Feedback Support System is expected to have. This needs to be highlighted that end users are often not expected to able to directly come up with the functional requirements of the complex system, such as the Feedback Support System, as this would usually require a system development insight that is normally missing at the client side. However, the P.D.Eng. trainee developed a series of questions based on his initial vision of the system to determine what functions are expected in the system. The set of questions is presented in Section 3.2. Also, during this phase, an analysis of feedback types was conducted. This is because for Feedback Support System to be able to provide automated cues to instructors for POAs, it is important to determine (1) which feedback types are being often provided to trainees, and (2) what are the priorities of different feedback types. The priorities are important because given the limited timeframe of this project, it was not feasible to develop automated cues for all the feedback types. Therefore, the priorities were used to rank

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feedback types and then only the types ranked higher than 4 were considered for the development. This is explained in detail in Section 3.3.

In Phase 3, the functional requirements are used to design a conceptual model of the system. This phase resulted in a model that indicates the type and number of modules (i.e., sub-systems such as motion tracking, head tracking, VR environment, etc.) that are needed to provide the functions identified in the previous phase. The conceptual model was later used as a guideline to explore and investigate various hardware and software alternatives (e.g., GPS and Ultra-Wideband as part of the motion tracking module) that can be used in the system. The details of this phase are presented in Chapter 4.

Phase 4 was dedicated to the development of technical system architecture. This was done by comparing different hardware and software alternatives, which were identified in Phase 3, and identify the more efficient options for each module of the system. During this phase, the alternatives are assessed and compared against the high-level system requirements set by the client. For instance, GPS and Ultra-Wideband were compared with respect to accuracy, reliability and cost to determine the most viable option for the system. The outcome of this phase was a detailed system architecture that outlines the structure of the Feedback Support System. In other words, in this phase, the research committed to the most efficient options among all the alternatives for different modules of the system. The system architecture was then used to implement the system. The details of this phase in presented in Chapter 5.

In the next step, i.e., Phase 5, a prototype system was developed. This was done by developing individual modules of the system and then integrating them at the end. The implementation phase was tightly intertwined with Phases 6 and 7 in Figure 2. This was because different modules needed to be first tested and verified to make sure they deliver their expected functions, i.e., Phase 6. To make this happen, a debugging tool was developed to verify different modules of the prototype in each development stage. The detail of this tool will be discussed in detail in Section 7.1. Next, all modules were assembled in Phase 7. The assembled system was tested and verified to make sure the system delivers the expected functions. The testing of the system was first done in the lab environment on scaled equipment and later at SOMA college on actual equipment. Phases 5 to 7 needed to go through several iterations for debugging and troubleshooting. The outcome of these phases was a verified system that is capable of delivering the expected functions. The details of these phases are presented in Chapter 6.

In Phases 8 and 9, the verified prototype was validated by implementing it on a training session at SOMA College. During this session, the performance of an operator was monitored and then visualized. Then, a workshop was held with a group of instructors and trainees to present the results and assess the extent to which the system meets the user requirements, which were identified in Phase 1. As will be discussed in Chapter 7, in the workshop instructors learned about how the prototype needs to be set up, how it will operate, and how it can assist them in evaluating the trainees' performances. Also, the instructors were walked through the developed GUI to help them assess the user-friendliness of the system. A questionnaire was prepared to allow instructors to evaluate the prototype with respect to different client's requirements (i.e., assessment criteria). The outcome of these two phases was a validated prototype and a set of recommendations for the further development of the system in the future.

In the end, the P.D.Eng. trainee reflected on the entire process to identify lessons learned, limitations and recommendations for the future of the Feedback Support System. On top of the present report, the P.D.Eng. trainee prepared two additional documents, namely (1) a user manual that outlines how

the system needs to be set up and used. This user manual takes the readers through the prototype setup steps and the user interface of the software. This manual can be used by SOMA instructors, or any other interested party, to implement the prototype for training sessions; (2) a technical guideline that presents the development detail, the coding details, and grueling technical nuances. This document can be used by system developers who want to learn about the development detail and perhaps further improve the prototype. These two documents are submitted as addenda to this report.

3   Functional Requirements of the Feedback Support System

This chapter outlines the functional requirements of the system. As explained in Chapter 2, at this phase of the research the high-level client's requirements were translated into a set of functional requirements. To this end, first, the stakeholder analysis is performed to identify the interests of different parties in this project. This will appear in Section 3.1. Then, a workshop was held with instructors from SOMA College to indirectly determine the functional requirements. As mentioned earlier, the identification of the functional requirements should be done indirectly because the end-users normally lack the technical insight to be able to explicitly identify the required functions from the system. In this case, a set of guiding questions were formulated based on the initial vision of the P.D.Eng. trainee to identify what specific functions must be provided by the system. The details of these questions and the workshop will be presented in Section 3.2.

3.1   Stakeholder Analysis

Table 2 shows the stakeholders involved in this project, 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.

Table 2. Involved stakeholders and their needs from various views

View	Stakeholder	Need
Enterprise	University of Twente	Helping industry to reduce excavation damages and injuries by identifying the limitations of the current practice and trying to tackle them
	Project Client (e.g., Rijkswaterstaat)	Less damage and safety hazards on the construction site
Business Management	SOMA College	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
Business Operation	Instructor	Use their limited time efficiently to make sure trainees make good progress with their training
	Trainee	Acquiring the required professional skills as soon and good as possible

The University of Twente (UT) is involved in the project from an enterprise perspective. Its ultimate goal is to help the industry reduce excavation damages as much as possible. To this end, UT wants to first identify the limitations of the existing operator training program and then tackle them by means of proposing and showcasing innovative technological and organizational solutions. In the context of the Feedback Support System, UT requires the Feedback Support System to be developed in a systematic manner to properly address the needs of the industry. UT also wants to make sure the proposed system is properly tested, verified and validated.

The system provides a new way for training the operators of construction equipment which affects the excavation contractors and project clients (e.g., Rijkswaterstaat). Incidents on construction sites are

undesired for the contractors and clients because it delays the delivery of their projects and costs money. Most of these incidents are because of not considering safety instructions while operating with the construction equipment. Therefore, the contractors try to hire operators that have ready to market skills that are provided by an optimal training program. Similarly, project clients prefer to collaborate with contractors that have highly skilled operators.

The project directly affects the instructors and the trainees at SOMA College which are the main actors in a vocational training program. On-equipment training sessions provide an environment for instructors to directly supervise the trainees, to give them feedback, and observe how trainees enhance their operation based on the feedback. Instructors are willing to efficiently use their time during these sessions to provide more beneficial feedbacks to trainee. Trainees are also eager to comprehend more clearly these feedbacks to quickly acquire the skills they need for their future career as construction equipment operators.

3.2 Functional Requirements Analysis

Following the above stakeholder analysis, the candidate conducted a workshop (4 instructors, 2 educational support staff as shown in see Figure 3), and a series of informal interviews with SOMA instructors and managers to identify the functional requirements of the system. The scope of functional requirement analysis was limited to requirements from the *Business Operation* view. Ideally, the final solution's impact should be aligned with the goals of other views, however, no validation is performed to check this alignment because of the limited time during the P.D.Eng. project.

As stated above, the functional requirements had to be identified in an indirect manner, due to the lack of technical insights on the interviewees/workshop participants side. These interviews were mostly held in an informal manner to allow interviewees to use their creativity to come up with useful requirements that could have been left out of the initial vision of the candidate. Nevertheless, the P.D.Eng. trainee tried to formulate a set of guiding questions to steer interviewees toward thinking in terms of the functional requirements of the system. The guiding questions are presented in Table 3.

Figure 3. The workshop at SOMA College to determine the functional requirements

Table 3. Functional requirements of Feedback Support System identified through a series of guiding questions

	Guiding Questions	Purpose	Functional Requirement
1	What aspects of equipment need to be represented in the visual representation?	The answer to this question helps determine the types of sensors required to capture and monitor the equipment	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 4
2	What aspects of trainees need to be represented in the visual representation?	The answer to this question helps identify the types of sensors required to capture and monitor the performance of trainee inside the cabin	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
3	What level of detail and accuracy of the visual representation of trainees' performance is considered sufficient for providing feedback?	The answer to this question would further guide in the selection of the type and number of different sensing technologies required to generate the visual representation of trainees' performance	Given that the focus of the accuracy is on the position of bucket tip with respect to the ground, the system is expected to have an accuracy of about 2 centimeters. Additionally, the rotation accuracy should be 1° with a drifting error of 1 °/hour. The positioning accuracy needs to be in the order of 3 meters. The visualization of the performance must also be smooth. This can be translated to requirements for the data capture frequency of at least 60 Hz
4	What aspects of the context of the operation (i.e., surrounding environment) need to be represented for the feedback?	This question would help determine types of sensors required to capture elements of the surrounding environment (e.g., soil, other equipment, buildings, etc.)	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.
5	During the feedback sessions, what aspects of the trainees' performance are being analyzed?	This question would help determine what kind of automated analysis can be applied on the performance to provide the instructors with relevant attention points for providing feedback	The system should help analyze certain aspects of the trainee's performance in terms of automated cues to POAs for the instructors. These aspects are explained in details in Table 3
6	When is the feedback to each trainee expected to be delivered?	This question is important to decide whether the system should be real-time or offline	The system is not required to be real-time. The instructors would want to give feedback to students after training sessions
7	How much time do instructors envision to spend on reviewing the feedback of each trainee?	This question would help better design the GUI of the system and how instructors would need to interact with the system	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)
8	How would instructors expect to provide feedback?	This question would specifically help determine the medium of feedback (audial, visual, textual, etc.)	The system should enable at the very least timestamped textual feedback
9	How are trainees expected to interact with the feedback system?	This question helps design the GUI of the system and determine the features required for the interaction of trainees with the 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

As shown in Table 3, a set of functional requirements were identified based on the responses provided by SOMA instructors and representatives of management. According to these functional requirements, the system must:

1. Capture the motion of all degrees of freedom of construction equipment, as shown in Figure 4;
2. Track the head pose of the trainees (mainly the rotation) inside the cabin to track their shoulder check tendency;
3. Offer visualization with the accuracy of a few centimeters (measured in terms of the position of the bucket tip as shown in Figure 4) and frame rate of at least 60 Hz. Also, the rotation accuracy must be 1° with the drifting error of no more than 1 °/hour. The positioning accuracy (i.e., translation of excavator in Figure 4) should be 3 meters.
4. Can represent the pose (i.e., location and orientation) of other equipment in the vicinity;
5. Provide automated cues to instructors to signify the POAs for feedback;
6. Offer offline visualization;
7. Have a user-friendly GUI for the instructor to interact with the virtualized training site (3D navigation and the training session time travel);
8. Provide a feature for the instructors to annotate their feedback in terms of timestamped text;

An additional good-to-have functional requirement was also identified. According to this requirement, the system should enable trainees to use the same virtual environment to practice the operation based on the provided feedback using joysticks.
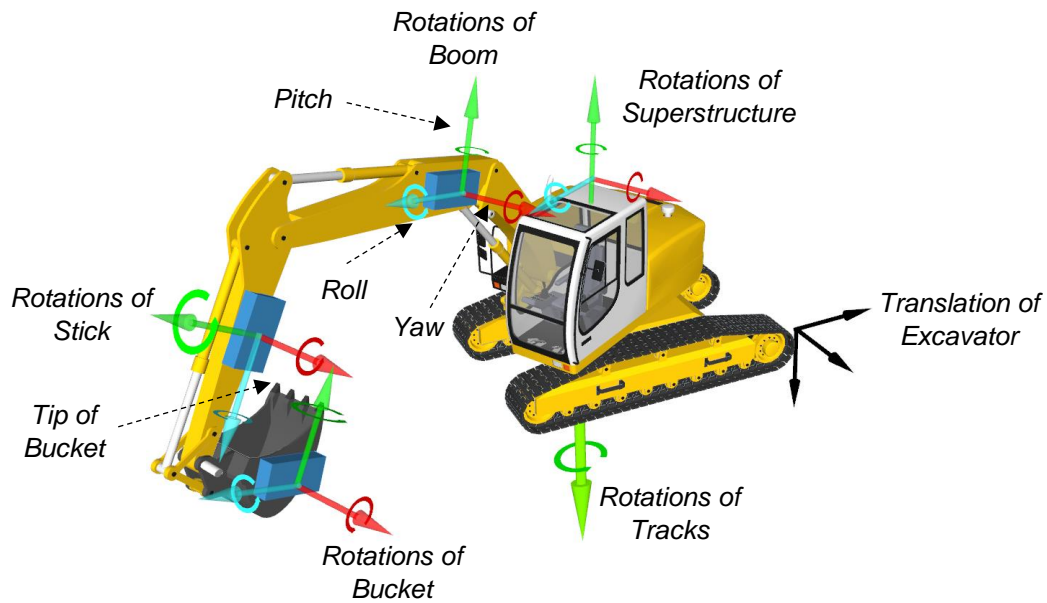
Figure 4. Required degrees of freedom for visualization of an excavator

3.2.1   Feedback Typology; determining the scope of automated cues to points of attention

Of the above functional requirements, requirement 5 needed more elaboration. This is because instructors provide a myriad of feedback types to trainees and for the system to be able to generate automated cues to POAs, it is important to identify the typology of feedback provided to trainees. Additionally, given the limited time available for this project, it was not feasible to implement automated cues for all types of feedback in the system. Therefore, it was important to determine the

priorities of different types of feedback. The priorities were used to rank the feedback types and then only the top types with priority greater than 4 were considered for the automated cues.

To determine and prioritize the feedback types, the P.D.Eng. trainee asked the workshop participants about the type of feedback provided to the trainees. To stimulate the discussion and to better steer participants to think in terms of feedback types, the P.D.Eng. trainee proposed a set of ten feedback types to the instructors based on the review of literature, observation of on-equipment training sessions and brainstorming with UT supervisors. During the workshop, instructors also came up with new feedback types that they deemed necessary. The proposed feedback types are shown in Table 4.

Table 4. Feedback Typology and required data for automated detection

Proposed by	Feedback Type	Description	Required Data
P.D.Eng. Trainee	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 head rotation
	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	Operator eye movement
	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	Full motion of all the equipment
	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.	Angular velocity of arm's joints
	Bucket movement smoothness	The excavation performance of operators depends on how smooth they move the bucket.	Angular velocity of excavator's joints
	Bucket load	This feedback type focuses on the amount of soil in bucket. If this amount exceeds from a certain threshold which depends on the excavator specifications, the maneuver is not efficient	Mass of the soil in the bucket
	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	Geometry of trench
	Operator drowsiness level	This metric determines the drowsiness level of operators while they are working with the excavator	Operator's biosignals (e.g. Skin electrical conductivity)
	Operator stress level	This feedback type addresses the stress level of trainees while working with the excavator	Operator's biosignals
	Axes movement speed	This feedback deals with how fast operators move the excavator arm in each maneuver	Angular velocity of excavator's joints
Workshop Participants	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	Acceleration of excavator tracks
	Bucket loading distance	This feedback concerns the amount of pressure on the hydraulic cylinders while trainees dig. When trainees lift the loaded bucket, if the bucket is too far or close to the tracks, more fuel is consumed.	Full motion of the equipment

The prioritization of the feedback type was conducted by seeking the opinion of the instructors who attended the workshop. The instructions were asked to score the priority of each feedback type using a five-point scale, where 1=Not Useful, 2=Partially Useful, 3=Useful, 4=Very Useful, 5=Crucial. A sample of the scoring sheet is presented in Appendix 2: Prioritization Form. Then, the mean of the scores given by instructors is calculated to rank the feedback types in terms of priorities. Figure 5 presents the results of the ranking of feedback types.
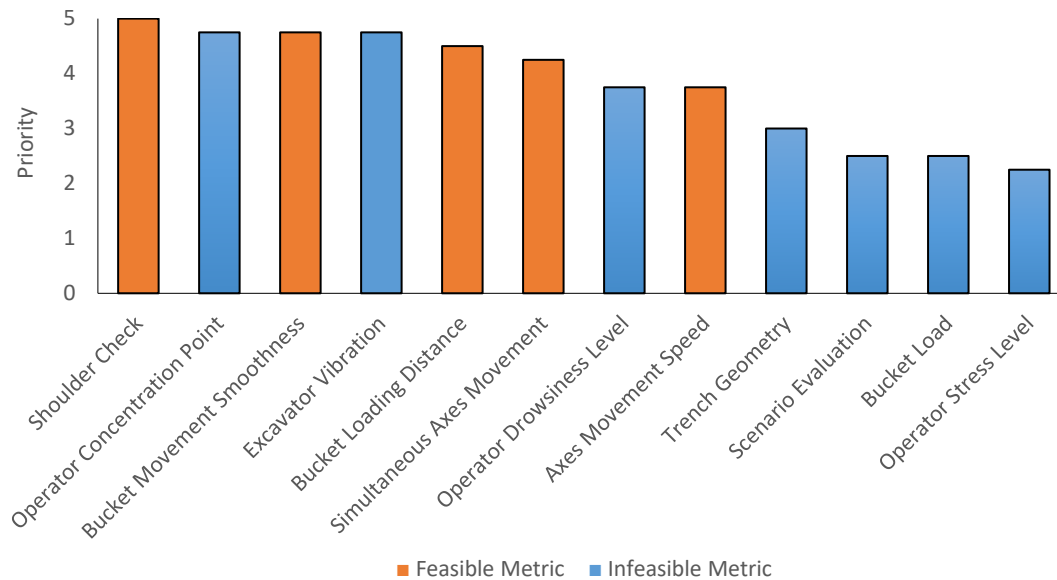
Figure 5. The feedback type priority

Given the available time for this project and the ranking presented in Figure 5, four feedback types were selected for the implementation in the Feedback Support System. Of the top 8 feedback types, two types, namely, operator concentration points and excavator vibration, required sensor types that were additional to those required for motion capturing of the excavator and trainee. Therefore, it was consensually (together with the instructors) decided to skip these two feedback types. Accordingly, the final list of feedback types that will be supported by the automated cues to POAs for instructors is as follows:

1. *Shoulder check;*
2. *Bucket movement smoothness;*
3. *Bucket loading distance;*
4. *Simultaneous axes movement;*

On top of these feedback types, an additional type was later on introduced during the project by experts, which is stability check. Since this feedback type was not part of the discussion in the workshop, it is treated as an additional. In this feedback type, the stability of the excavator is determined based on the relative position of the bucket tip with respect to the excavator tracks.

3.3 Summary

This chapter provided an overview of the functional requirements of the system. These functional requirements were identified through a set of informal interviews and a workshop with the instructors and managers of SOMA college. In summary, the Feedback Support System is expected to meet the following functional requirements:

1. Capture the motion of all degrees of freedom of the excavator, as shown in Figure 4;
2. Track the head pose of the trainees (mainly the rotation) inside the cabin to track their shoulder check tendency;
3. Offer visualization with the accuracy of a few centimeters (measured in terms of the position of the bucket tip as shown in Figure 4) and frame rate of at least 60 Hz. Also, the rotation accuracy must be 1° with the drifting error of no more than 1 °/hour. The positioning accuracy (i.e., translation of excavator in Figure 4) should be 3 meters.
4. Can represent the pose (i.e., location and orientation) of other equipment in the vicinity;
5. Provide automated cues to instructors to signify the POAs for feedback. Five feedback types were selected through a systematic ranking of possible feedback types by SOMA instructors (as shown in Figure 5). These feedback types are:

   a) *Shoulder check*
   b) *Bucket movement smoothness*
   c) *Bucket loading distance*
   d) *Simultaneous axes movement*
   e) *Stability check*

6. Offer offline visualization;
7. Have a user-friendly GUI for the instructor to interact with the virtualized training site (3D navigation and the training session time travel);
8. Provide a feature for the instructors to annotate their feedback in terms of timestamped text.
9. Provide a feature for the replay of annotated visualization for trainees.
10. Enable trainees to use the same virtual environment to practice the operation based on the provided feedback using joysticks[1].

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[1] This requirement was mentioned as a good-to-have by experts.

4 Functional Design of Feedback Support System; Conceptual Design

After identifying the functional requirement of Feedback Support System, a conceptual model of the system was developed. This conceptual model aims to indicate how different required functions can be integrated into a coherent system and determine what are the alternatives for delivering these functions.

It should be highlighted that while video recording can be used to provide instructors with a means of reviewing trainees' performances and giving feedback, this does not meet the functional requirement 7, according to which instructors need to be able to freely navigate in the visual scene and view the training session from different viewpoints. Additionally, video recording is debased by the occlusion problem. Therefore, the proposed conceptual design is built entirely around the idea of using virtual reality as a basis for the Feedback Support System.

Figure 6 shows an overview of the functional design of the Feedback Support System. This figure illustrates the hardware and software components required to deliver these functions. As shown in this figure, the *Data Collection* module in the system is dedicated to collect motion data of the excavator (i.e., translation and rotation) and trainees (i.e., head rotation). To this end, tracking technologies are needed to capture (1) excavator location (i.e., x, y, z in Figure 7), (2) excavator pose (i.e., $\psi_1, \psi_2, \psi_3, \theta_1, \varphi_1$ in Figure 7), and (3) trainee's head pose (i.e., θ_2 in Figure 7). This module addresses the functional requirements 1 and 2 shown in Section 3.3.

Once the location and the pose of the excavator and pose of trainee's head are known, the data need to be integrated, time-stamped, and synchronized in *Data Preparation* module. The integration and synchronization of data need to be done by a processor. Once the data is synched, the data need to be stored. This would require a means for storage of data (e.g., cloud storage or a local storage). Like the previous module, these steps are also performed during the training session. This module addresses functional requirements 1 and 2 of the system.

In *Data Visualization* module and after the training session is over, the stored data need to be visualized in a virtual scene. This would require a visualization environment where necessary developments can be made to link the collected data to a 3D model of equipment and trainee. These 3D models can be designed from scratch or retrofitted from available online 3D models (once for every equipment type). Linking of the data, in this context, means associating the state of different degrees of freedom or joints (shown in Figure 7) in the 3D model with the corresponding state of the actual equipment or trainee captured in the collected data at every instance of time. By doing so, this module is able to address functional requirements 3, 4, and 6, as shown in Section 3.3.

In *Performance Analysis* module, the system analyzes the performance of the trainee and automatically detects POAs and provides cues to the instructor about parts of the training that require the instructor's attention. This module requires a set of algorithms to identify the POAs based on the feedback types identified in Section 3.2.1. These algorithms can be combined into an analyzer module that runs inside the visualizer and signifies POAs. This module concerns the functional requirement 5 of the system. The details of these methods will be presented in Chapter 5.
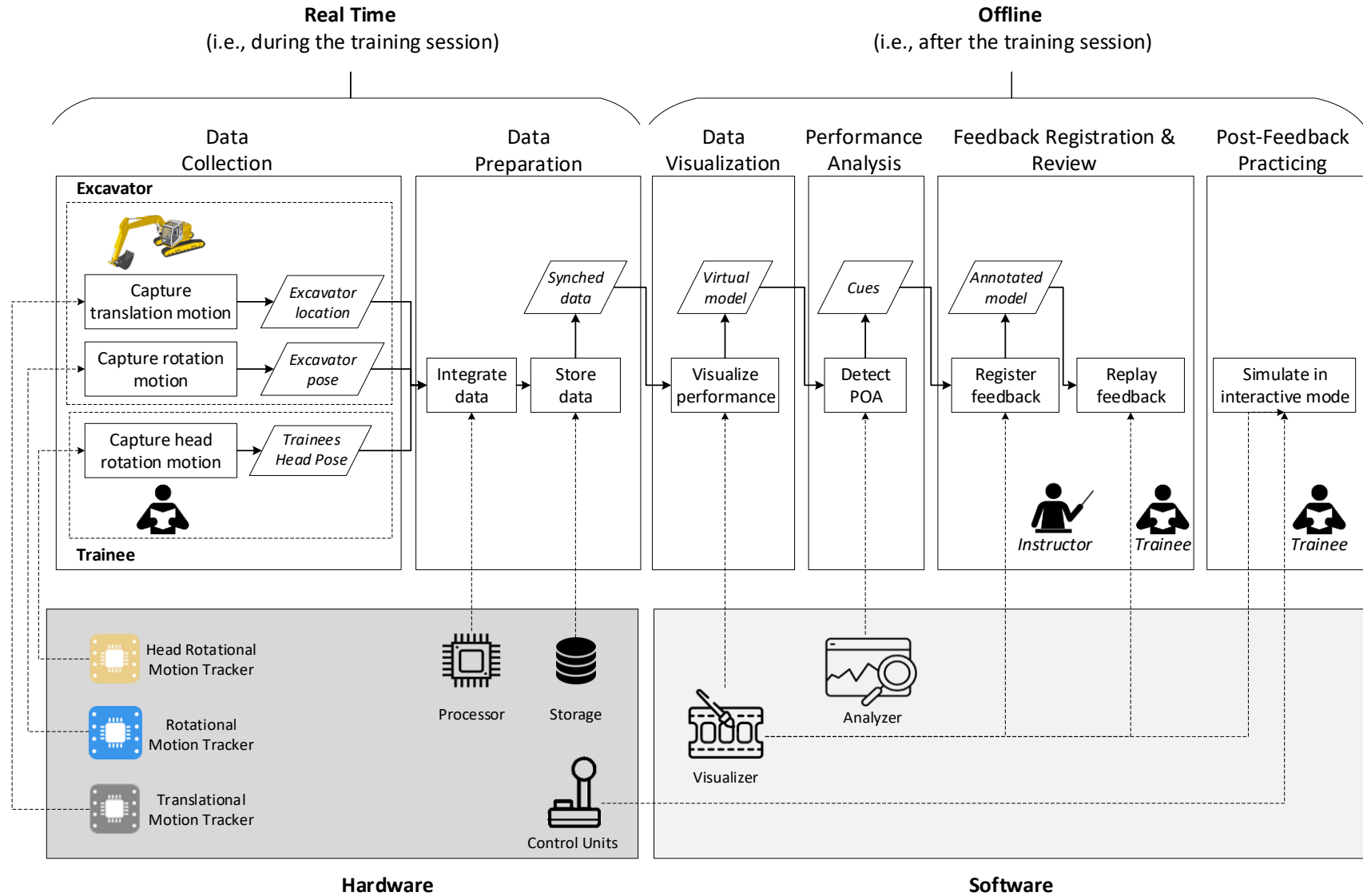
Figure 6. Feedback Support System conceptual design

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In *Feedback Registration and Review* module, the instructor reviews the performances of trainees offline and pinpoints points of improvements (such as not doing a shoulder check while the equipment is moving in reverse) based on (1) the provided POAs, and (2) his/her visual review. This can be done through a custom-made GUI that allows navigation and review of the trainee performance from any Points of View (POV). The instructor can insert some notes for the trainees and eventually export the annotated virtual scene for the trainees. Next, the trainees will receive the annotated virtual reality scenes and can navigate through their training sessions and feedback provided by the instructor. Using the feedbacks, the trainees have a clearer idea about where to focus on for the next training sessions. This module addresses functional requirements 7, 8, and 9 of the system.

In *Post-Feedback Practicing* module, the visualizer can be switched to interactive mode to enable trainees to use some control units (e.g., joysticks) to practice their tasks in the virtual environment. This module is designed to satisfy the functional requirement 10 of the system.

Figure 7. Data required to represent motions of excavator and trainees head

5 Technical Design of Feedback Support System; System Architecture

For different hardware and software components shown in Figure 6, there are several alternatives. These alternatives are compared with each other ba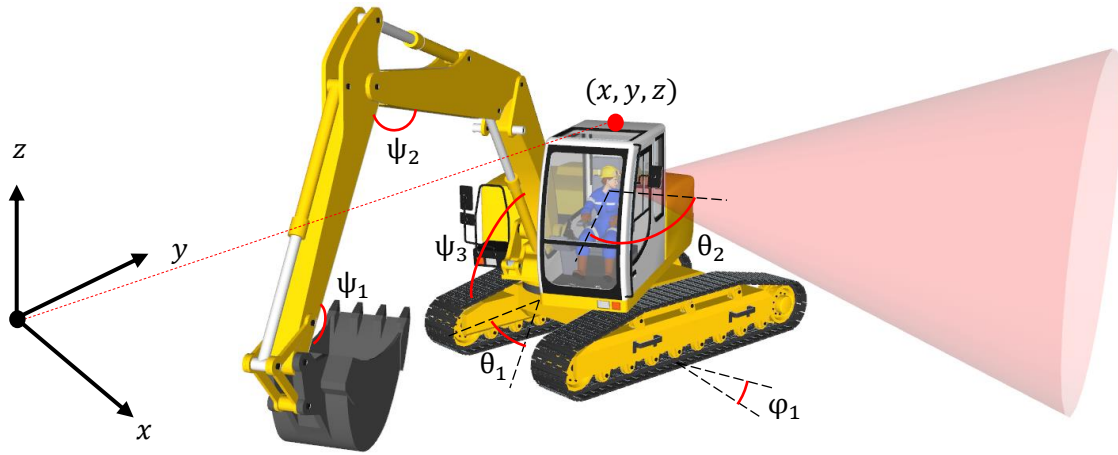sed on the high-level requirements set by the client (see Section 1.4). These high-level requirements are usefulness, accuracy, reliability, robustness, affordability, and user-friendliness. An additional criterion used for the comparison of different alternatives is the development time. This requirement was not set by the client but play a major role in determining what is feasible within the course of this project.

5.1 System Alternatives

Table 5 presents all the possible alternatives for hardware and software components of the system.

5.1.1 Translational Motion Tracker

This component is responsible for determining the location of the equipment in the training site. The UWB and RFID technologies are designed for indoor localization applications and hiring them for outdoor applications requires lots of development and setup effort. GPS technology is originally designed for outdoor applications. While it has lower accuracy in comparison with UWB and RFID technologies, it requires a significantly lower development effort.

5.1.2 Rotational Motion Tracker

This component is used to define the pose of the equipment by measuring the rotation of its rotary joints, as shown in Figure 7. For tracking the equipment's rotational motion, IMU sensors can be employed which has high accuracy and a high sampling rate. An IMU is an electronic chip that can measure the rotation of an object in 3 perpendicular directions. Unlike vision-based trackers, IMUs are not affected by the field of view, which is essential in the scope of this project. Even so, magnetic tracking systems have better accuracy than IMUs, they are designed for indoor application and they are very expensive.

5.1.3 Head Rotational Motion Tracker

This component is used to check the situational awareness of equipment operators (e.g. doing a shoulder check) by tracking their head pan angle. Vision-based trackers are non-intrusive systems for tracking the head pan angle, but they are not robust in different illumination conditions while the trainees are working in an outdoor environment. Although IMUs are intrusive head tracking systems, they are more robust and they require less development time.

5.1.4 Processor

This component serves several tasks, including integration, synchronizing, and storing sensory data. Embedded PCs are one of the options for processing the sensory data in real-time, however, they are more expensive and consume more energy in comparison with single-board computers.

5.1.5 Storage

This component provides a medium for logging the synchronized sensors data. The collected data can be stored in local storage or cloud storage. Nevertheless, it is not optimal to store the data on cloud storage due to its enormous development and maintenance effort. Besides that, the reliability of local

storage is sufficient in the Feedback Support System context which means its probability of failure during a 4-hour training session is less than 1%.

5.1.6 Control Units

This component generates an interactive VR environment for trainees to practice with an excavator after getting feedback from instructors. This interaction can be implemented via VR simulator platforms which have high immersion to visualize the commands of trainees with high fidelity. However, all the training simulator platforms in available the market are closed-source which require lots of time to be integrated with the Feedback Support System. So, a game controller solution is used instead to provide the same functionality with lower development effort.

Table 5. Available alternatives for the components of the Feedback Support System

Type	Function	Alternative Solutions	Pros	Cons
Hardware	Translational Motion Tracker	Global Positioning System (GPS)	- Low setup effort - Low development time	- Low accuracy (Not *Accurate*) - Very low sampling rate
		Ultra-Wideband (UWB)	- High accuracy (*Accurate*) - High sampling rate	- Very high setup effort - High development time
		Radio Frequency Identification (RFID)	- High accuracy (*Accurate*) - High sampling rate	- Moderate setup effort - High development time
	Rotational Motion Tracker	Inertial Measurement Unit (IMU)	- High accuracy (Very *Accurate*) - High sampling rate	- Drifting error (Not *Accurate*)
		Vision-based Tracking	- Remote sensing (*User-friendly*)	- Moderate accuracy (*Accurate*) - Moderate sampling rate
		Magnetic Tracking System	- Very high accuracy (very *Accurate*) - High sampling rate	- Very expensive (Not *Affordable*)
	Head Rotational Motion Tracker	Inertial Measurement Unit (IMU)	- High accuracy (Very *Accurate*) - High sampling rate - Low development time	- Intrusive (Not *User-friendly*)
		Vision-based Tracking	- Non-intrusive (*User-friendly*)	- Moderate accuracy (*Accurate*) - Moderate sampling rate - High development time
	Processor	Single-board Computer	- Cheap (*Affordable*) - Low energy rate	- High development time
		Embedded PC	- Low development time	- Expensive (Not *Affordable*) - Moderate energy rate
	Storage	Local Storage	- Low development time	- Moderate reliability (*Reliable*)
		Cloud Storage	- High reliability (Very *Reliable*)	- High development time
	Control Units	Game Controller	- Low development time	- Low immersion (Not *Accurate*)
		Simulator Platform	- High immersion (*Accurate*)	- High development time
Software	Analyzer	Hard Computing Method	- Low development time - High response time	- Moderate accuracy (*Accurate*)
		Soft Computing Method	- High accuracy (Very *Accurate*)	- High development time - Moderate response time
	Visualizer	Game Engine	- Low development time	- Moderate reliability (*Reliable*)
		Graphics Application Programming Interface (API)	- High reliability (Very *Reliable*)	- High development time

5.1.7 Analyzer

The function is responsible for the automatic detection of POAs that guide instructors to focus on more important parts of the trainees' performance. The automatic detection function can be implemented based on hard computing methods (e.g. mathematical analysis) or soft computing methods (e.g. machine learning). Soft computing methods offer high accuracy for analyzing trainees' performance, but they require high development effort, which does not fit in the project schedule.
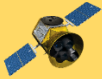
5.1.8 Visualizer

This component deals with the visualization and rendering of trainees' performance and instructors' feedback using computer graphics. Graphics APIs provide a highly flexible and reliable environment for visualization rather than game engines, but the visualization based on these APIs has a huge workload rather compared to game engines. The later drawback makes Graphics APIs an inappropriate option in the scope of this project.

5.2 System Architecture

Based on the comparison of different alternatives presented in Chapter 4, a set of choices have been made to develop the Feedback Support System. Table 6 is the morphological chart of the components of the Feedback Support System that presents an overview of these choices.

Table 6. Morphological chart of the Feedback Support System solution space

Function	Alternative solutions		
Translational Motion Tracker	GPS	UWB	RFID
Rotational Motion Tracker	IMU	Vision-based Tracking	Magnetic Tracking System
Head Rotational Motion Tracker	IMU	Vision-based Tracking	
Processor	Single-board Computer	Embedded PC	
Control Unit	Game Controller	Simulator Platform	
Storage	Local Storage	Cloud Storage	
Analyzer	Hard Computing Method	Soft Computing Method	
Visualizer	Game Engine	Graphics API	

As shown in Figure 8, the conceptual model of the system, which was presented in Figure 6, is updated to schematize the relationship between the design choices and the architecture of the system. The system consists of 6 modules, namely data collection, data integration, data visualization, performance analysis, feedback registration and review, and post-feedback practice.

5.2.1 Data Collection

As presented in Figure 8, the data collection consists of a GPS sensor, boom IMU, the stick IMU, bucket IMU, and the head IMU. The GPS sensor is responsible for tracking the translational motion of excavators. GPS is used to locate the position of the excavator in terms of latitude, longitude, and altitude. The set of the boom, stick, and bucket IMUs are responsible for tracking the rotation motion of the arm system. In addition to these IMUs, an additional IMU is needed to capture the relative angle between the superstructure and tracks. Finally, the head IMU is responsible for tracking the trainees' head rotation. This IMU can be mounted on a cap or a hardhat.

Altogether, these IMUS measure angles shown in Figure 7. It is worth noting that when the excavator swings, the boom, the stick, and the bucket swing accordingly and therefore all the IMUs attached to the arm system can measure the swing angle equally. As a result, there is no need to mount another IMU on the cabin to measure the swing angle.

5.2.2 Data Preparation

For the collected data to become integrated in the single-board computer, they must be transmitted to this computer, which is located inside the cabin. It is in favor of system robustness and reliability to use wired communication between IMUs and the computer. However, given the high degrees of relative mobility between the arm joints, running cables along the arm is logistically challenging. Therefore, a strategic decision is made to keep the wired connection between (1) bucket and stick IMUs, and (2) GPS and computer. The remaining connections are designed to be wireless. To enable the wireless transfer of bucket and stick data, the stick IMU is designed as a wireless hub, that transmits the both data packets, as shown in Figure 8. The wireless communication between the IMUs on the arm and the computer uses Wi-Fi protocol, because of the longer range. The communication between the head IMU and the computer uses Bluetooth protocol.

The single-board computer integrates the collected data, synchronizes them, and timestamps them. Figure 9 schematically represents the data flow between the sensors and the single-board computer.

Data Collection

Single-board Computer

USB stick

IMU₃

Wireless Connection

GPS

Wired Connection

Wireless Connection

IMU₁

IMU₂

IMU₄

Wired Connection

Wireless Connection

IMU₅

Data Preparation

Arm Rotation

Excavator Translation

Head Rotation

Single-board Computer

Synched data

Data Visualization

Synched data

unity

Game Engine

Performance Analysis

Analyzer (algorithm)

Game Engine

Feedback Registration & Review

Trainee

Instructor

Post-Feedback Practicing

Trainee

Figure 8. Architecture of the Feedback Support System

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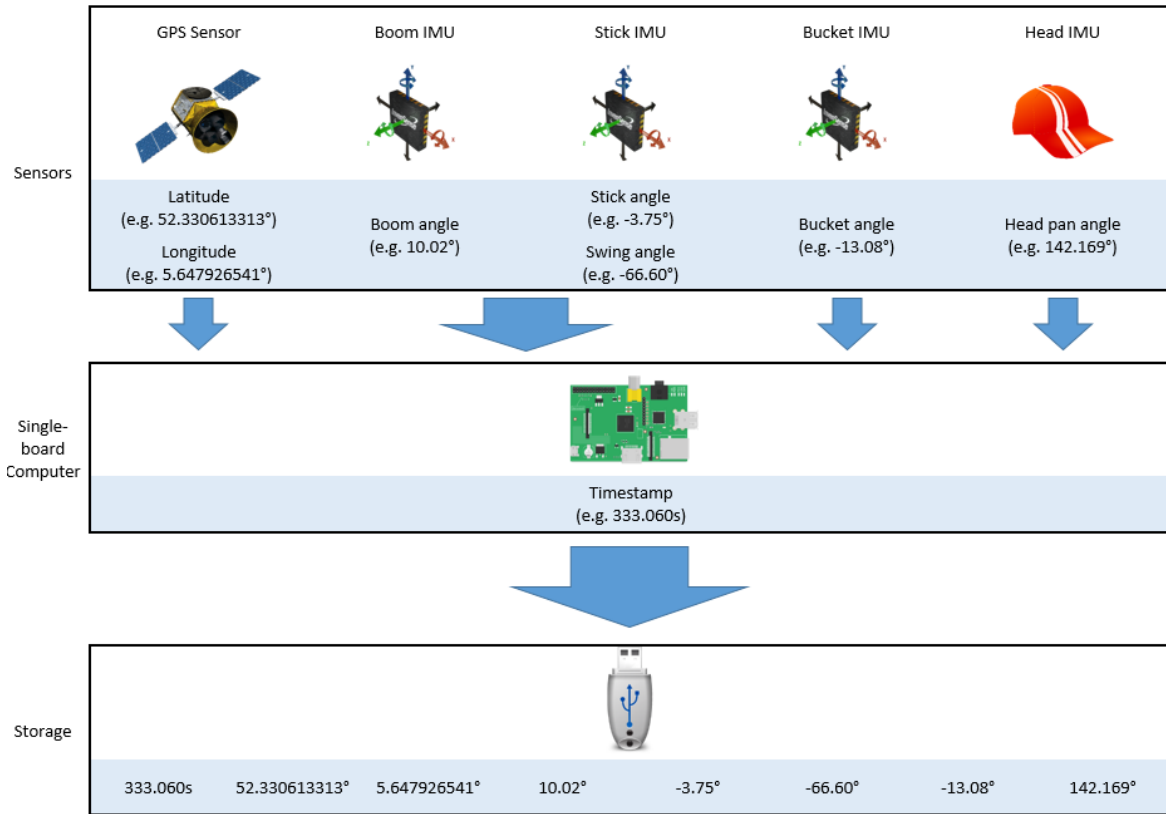
Figure 9. Dataflow diagram of Data Preparation module

5.2.3   Data Visualization

Once the synced data is stored into a USB stick, it should be manually transferred to the visualizer. The visualizer links the data the 3D model of the excavator. In the linking process, the motion data measured by each sensor is applied to its corresponding part in the 3D model. It is essential that the kinematic chain of the 3D model is correctly scaled to the kinematic chain of the real excavator. Otherwise, the motion of excavator (e.g. the motion of the bucker tip) in the virtual environment differs from its motion captured in reality. As shown in Figure 10, different parts of an excavator 3D model should be organized in the presented hierarchy to mimic the same kinematic chain of a real excavator. In Figure 10, by attributing the translational motion data to Joint 1 and linking the IMU data to the corresponding Joints 1, 2, 3, 4, and 5, the motion of the excavator can be visualized in the virtual environment.
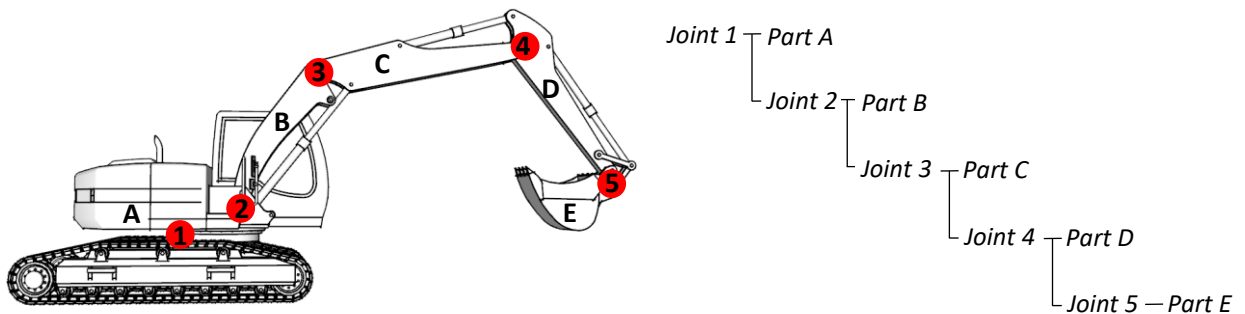
Figure 10. Example of 3D model preparation for virtualization

Besides the motion data linking, the virtual scene is created by generating a digital terrain model (DTM) of SOMA College training sites in Harderwijk, the Netherlands. The DTM is generated using Autodesk Infraworks in which the DTM region is specified by determining GPS coordinates. The generated DTM later is imported to the Unity game engine to be used as the virtual scene.

5.2.4   Performance Analysis

The system automatically evaluates the performance of trainees to indicate to instructors which parts of the performance need attention using cues. These cues support instructors to focus more on the periods of the performance where a significant event happened. Without these cues, instructors must view the whole training session for evaluation which may last about 4 hours. As mentioned in Section 3.2.1, five feedback types are supported in this system, namely bucket loading distance, shoulder check, bucket movement smoothness, simultaneous axes movement, and stability check.

Bucket loading distance

Loading the bucket if it is too far from the excavator or even too close to it requires more fuel consumption rather than when the bucket is in an average distance to the excavator. So, the loading distance is considered as a metric to determine the loading efficiency.

Figure 11. The efficient (green) and the inefficient (red) zones of lifting the loaded bucket

Figure 11 shows the efficient and the inefficient zones of lifting the loaded bucket. If the bucket is lifted in the green zone, the operation performs efficiently and if the bucket is lifted while it stays in the red zone, the operation performs inefficiently. The boundaries of these zones only depend on the excavator arm geometry and its degrees of freedom which can be found in the specification sheet of excavators provided by their manufactures. The flowchart of determining the bucket loading efficiency is presented in Figure 12.
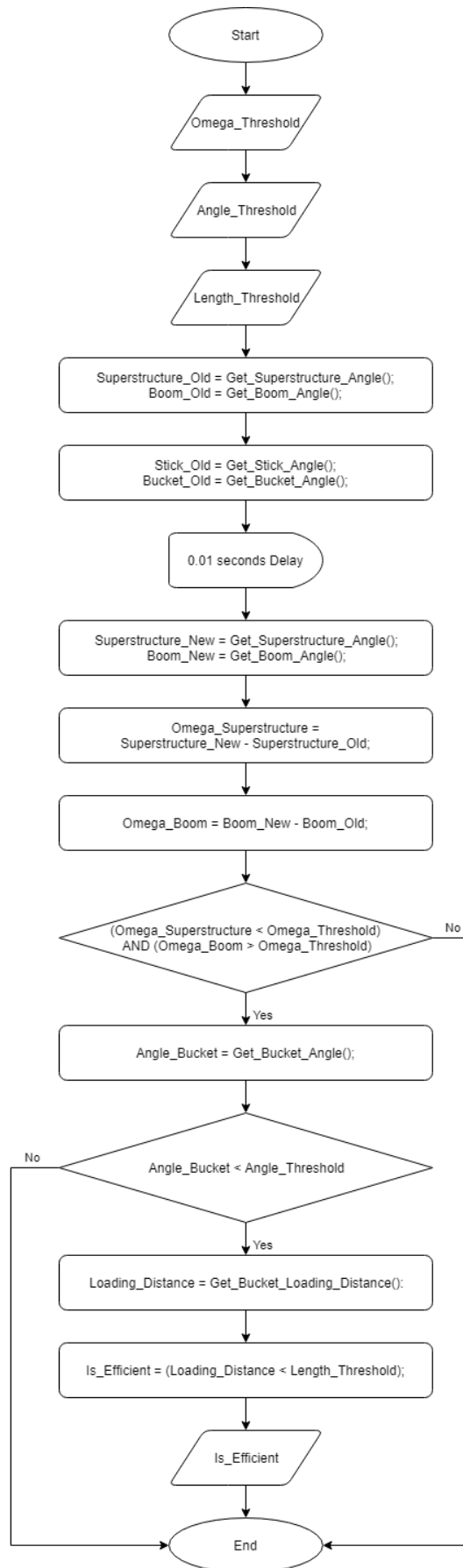
Figure 12. Bucket loading distance efficiency determination flowchart

Shoulder check

The shoulder check can be determined by measuring the alignment difference between the excavator moving direction achieved from the GPS sensor and the operator looking direction achieved from the head IMU. The flowchart of the shoulder check detection is shown in Figure 13.
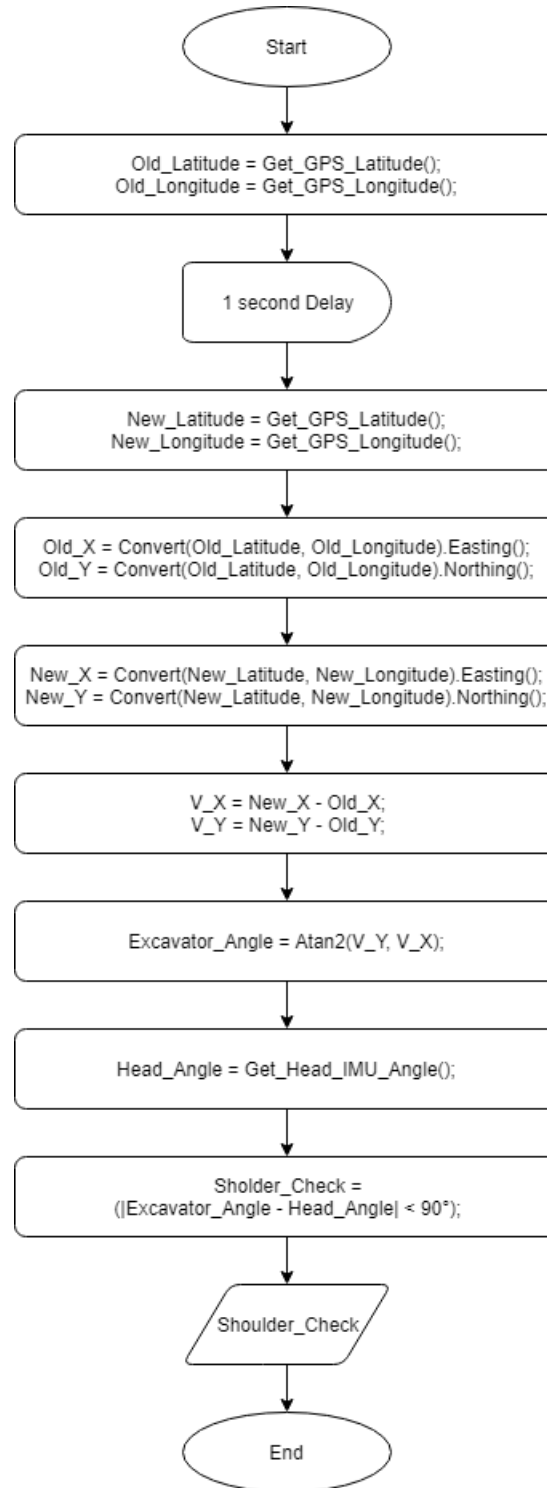
Figure 13. Shoulder check detection flowchart

Bucket movement smoothness

The smooth movement of the bucket is proportional to the motor skill level of trainees. The smoothness of a movement can be measured in several ways mentioned in Appendix 1. Feedback Support System employs three mathematical equations to determine the bucket movement is smooth or jerky as shown in Figure 14.
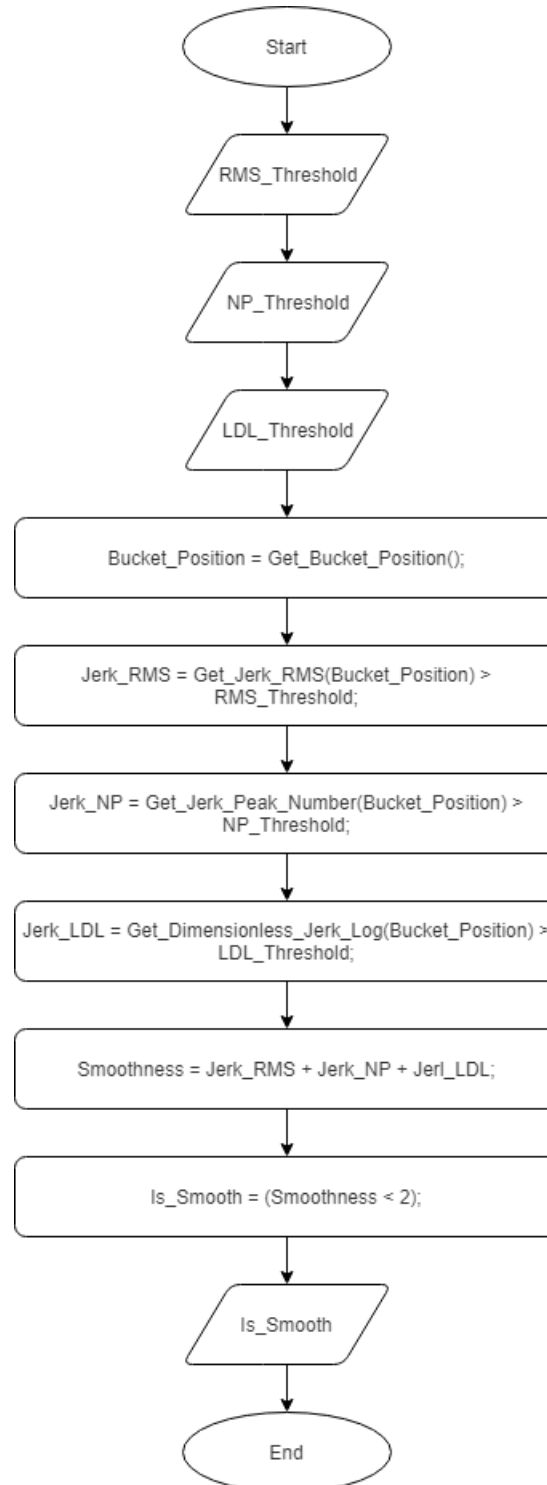
Figure 14. Bucket movement smoothness determination flowchart

Simultaneous axes movement

If the operator can move the boom, the stick, and the bucket at the same time, the performance is considered as a productive movement. The simultaneous axes movement is determined using the flowchart in Figure 15.
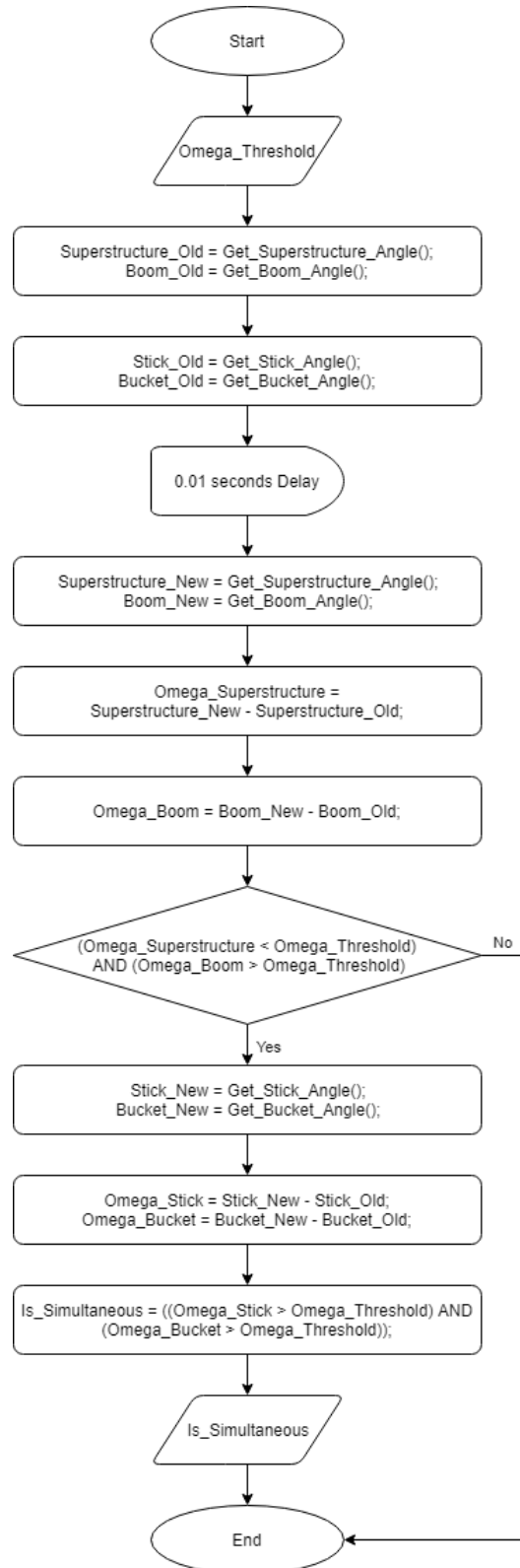
Figure 15. Simultaneous axes movement detection flowchart

Stability Check

This feedback type determines the excavator stability during the operation. The stability zone is defined as an elliptic cylinder which its dimensions depend on the excavator specifications (e.g. the track type), the arm length, and the bucket load. If the bucket lies outside the elliptic cylinder, it indicates that the excavator is unstable. If the bucket stays inside the elliptic cylinder, it means that the excavator is stable. The stability check flowchart is presented in Figure 16.
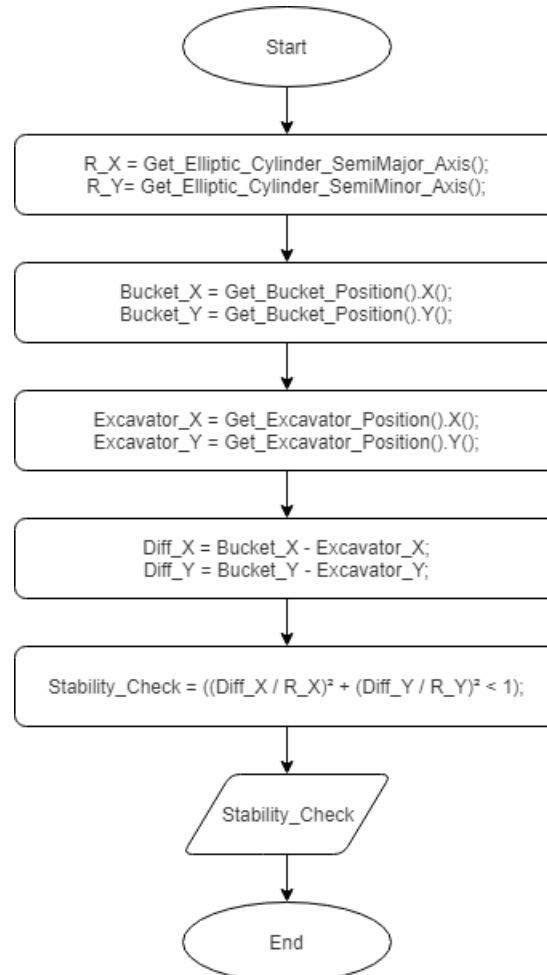
Figure 16. Stability check flowchart

5.2.5 *Feedback Registration and Review*

This module enables instructors to register annotated feedbacks, and it enables trainees to replay the visualization their training with the registered annotated feedbacks. Figure 17 illustrates the use case diagram of this module. The module has four main features, namely visualization playback, POA review, feedback registration, feedback review. Figure 18 shows the conceptual design of the GUI of this module.
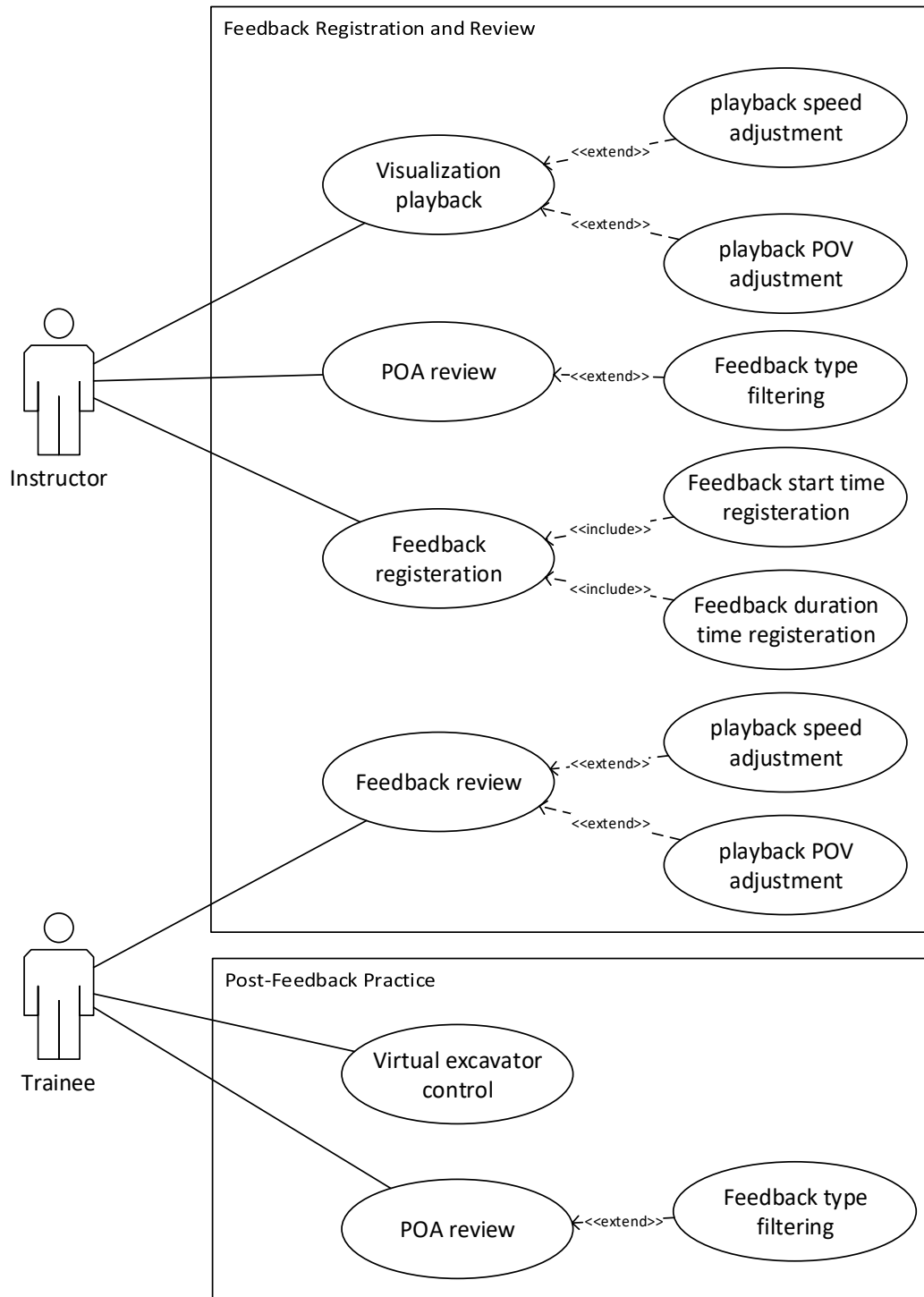
Figure 17. Use case diagram of Feedback Registration and Review and Post-Feedback Practice modules
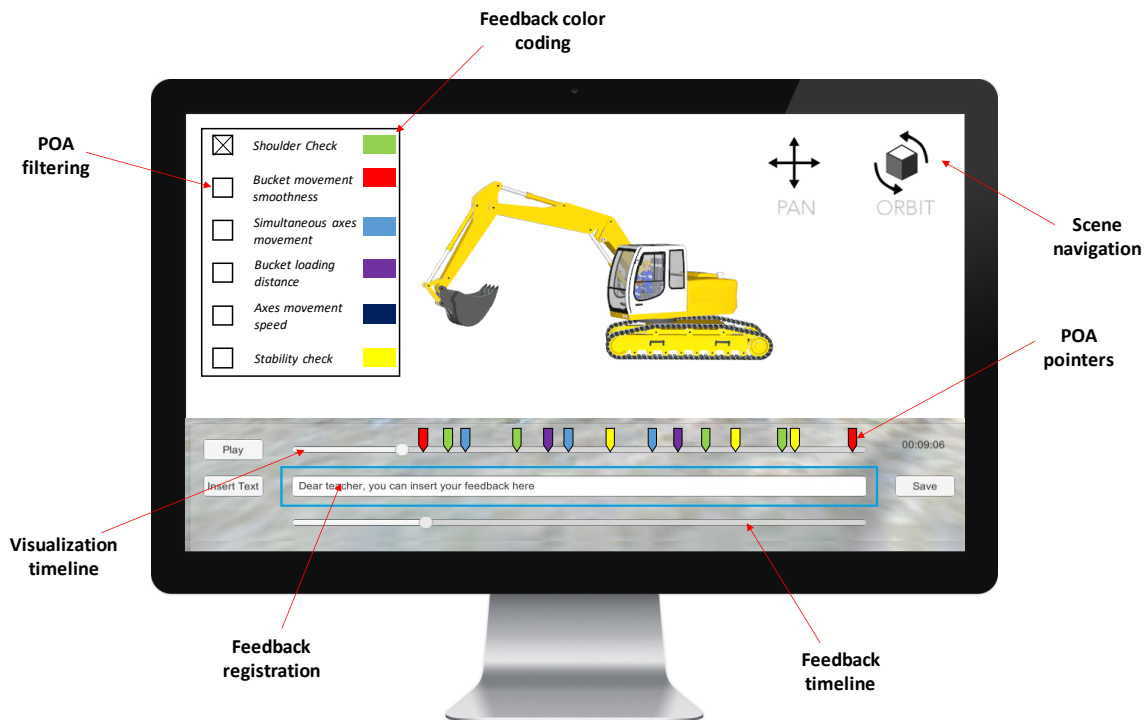
Figure 18. Schematic representation of the feedback support GUI

Visualization Playback

This feature is responsible for replaying the visualization of the performance. Instructors are able to playback the performance at different playback speeds. The GUI of this module offers an intractable timeline that can be used to change the playback speed as well as seeking through the visualization, as shown in Figure 18. Using this GUI, instructors can pause the visualization at any time they want. Also, the visualization environment provides the ability to navigate in the scene and view the performance from any POVs using pan, tilt, and zoom controls. The visualization can be played from an outsider perspective (instructor's perspective from outside the cabin) or from an insider perspective (trainee's perspective from inside the cabin).

POV Review

Instructors can go through the POVs generated by the system, as mentioned in Section 5.6. The POVs are marked on the timeline using a color-coding scheme, as shown in Figure 18. Additionally, the GUI of this module enables instructors to filter out a (set of) specific feedback types (e.g., shoulder check). This feature would allow instructors to focus on one type of feedback at a time.

Feedback Registration

Instructors can use the Feedback Support System to give trainees text feedback about their performance at any time in the software. As shown in Figure 18, instructors can select a moment, pause the visualization, write their feedback as a text, determine the duration they want the text to be displayed on the screen, and finally save the feedback. During the requirement analysis phase, the instructors stated that they prefer text feedback more than audio feedback.

Finally, trainees can use this module, and the GUI therein, to playback the annotated visualization. Similar to the visualization playback feature, the trainee can seek through the visualization, speed up/down and pause the playback. Trainees can navigate through the environment and adjust the POV as needed.

5.2.6   Post-Feedback Practice

The trainees can, after viewing their performance via the Feedback Support System, work on the instructors' feedback and practice in the system to improve their performance. The Feedback Support System has a simulator mode in which the trainee can use two joysticks to move different axes of the excavator in a virtual environment. The use case of this module is shown in Figure 17.

While it is not in the original functional design of the system, this module can also help instructors to visually demonstrate a correct way of performing a maneuver for trainees rather than explaining it to them verbally. The visual maneuver demonstration can reduce miscommunications between the instructors and the trainees during the training program.

6 Implementation

The architecture presented in Chapter 5 is implemented in a prototype system. The purpose of this prototype is to demonstrate the feasibility of the proposed design and assess its fitness to the purpose. On this premise, the prototype system, in no form or shape, is intended as a fully functioning system. In this chapter, a brief overview of the prototype is presented.

6.1 Hardware Components

Figure 19 presents an overview of the hardware components developed for the prototype. As explained in Section 5.2.1, the hardware of the system comprises 5 IMU sensors, a GPS sensor, and a single-board computer. During the development, SOMA instructors stated that the relative rotation between the superstructure of an excavator and the tracks of the excavator is not an important factor to evaluate trainees' performances. Therefore, the P.D.Eng. trainee decided to eliminate the IMU on the excavator track (i.e., IMU_5 in Figure 9). The remainder of the hardware system was developed precisely as explained in Section 5.2.1.

As explained in section 5.2.2, the connection between IMUs of the bucket and stick is wired (Figure 19c). Accordingly, the data of bucket IMU need not be transmitted wirelessly, and therefore no Wi-Fi transmitter is needed in the bucket IMU. This is why the casing of bucket sensor is smaller than the other two (stick IMU and boom IMU as shown in Figure 19d), which required Wi-Fi transmitters.

(a)

(b)

(c)

(d)
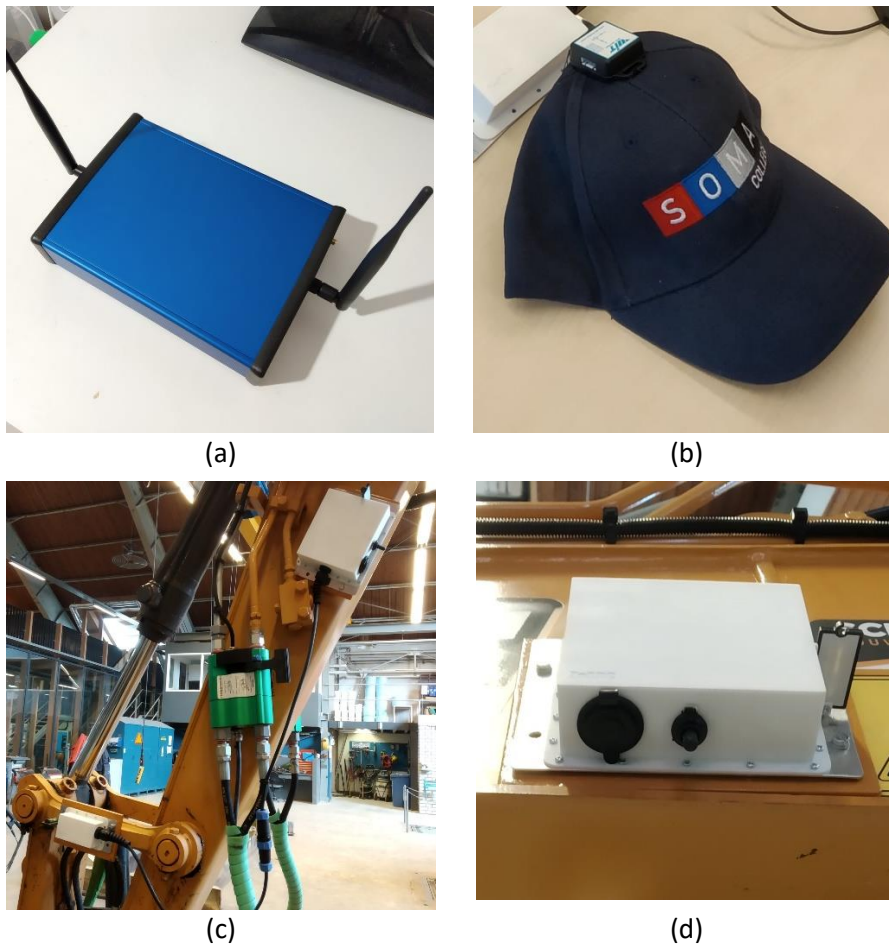
Figure 19. The hardware components of Data Collection module including (a) Single-board computer and GPS, (b) Head IMU, (c) Stick IMU and Bucket IMU, (d) Boom IMU

Figure 20 and Figure 21 show the configuration of sensors when installed on an excavator.

Figure 20. The configuration of the system's hardware on an excavator

Figure 21. A trainee wearing the head IMU inside the cabin

6.1.1   Hardware Protection (Casing)

As mentioned in Section 1.4, one of the main high-level requirements of the system was to ensure the system is robust. Given the inherent sensitivity of electronic devices to weather conditions, it was of paramount importance to ensure sensors are protected and designed as weatherproof as possible. Because the P.D.Eng. trainee could not find standard casings for the IMUs in the market, new waterproof casings were designed and manufactured, using 3D printing technology.

A watertight casing can be fabricated using injection molding but this method is not financially efficient if the casing is not going to be massively produced. For very small scale production, rapid prototyping

manufacturing, such as 3D printing, is more viable. There are different methods for 3D printing like Fused Deposition Modeling (FDM). To print a casing that is watertight, the Selective Laser Sintering (SLS) method is used, because it was the only 3D printer type available in UT during project development.

Figure 22 shows the developed casing. The stick IMU casing (Figure 22b) contains three openings; one for the power switch to turn on/off the sensor, one for the USB charger outlet to charge the sensor battery, and one for connecting the bucket sensor by a USB cable.

(a)

(b)
Figure 22. (a) Boom sensor waterproof casing with a USB charger outlet and an on/off switching button, (b) Stick sensor connection with the bucket sensor equipped with a cable gland

Waterproof on/off switches and waterproof USB charger outlets were bought off the shelf and mounted on the casing. To avoid water leakage from the cable opening, a cable gland is used in both the stick sensor and the bucket sensor (Figure 22b). A cable shielded with foil and braided copper was used to minimize the effect of electromagnetic noise between the sensors and USB communication.

Further, the casings were flanged at the bottom side to attach to an aluminum plate used for cooling. The flanged type attachment is commonly used in high-pressure pipelines for connecting the pipes. There should be a groove on the flange face that a gasket would lay down in that groove to enhance water tightness (Figure 23).
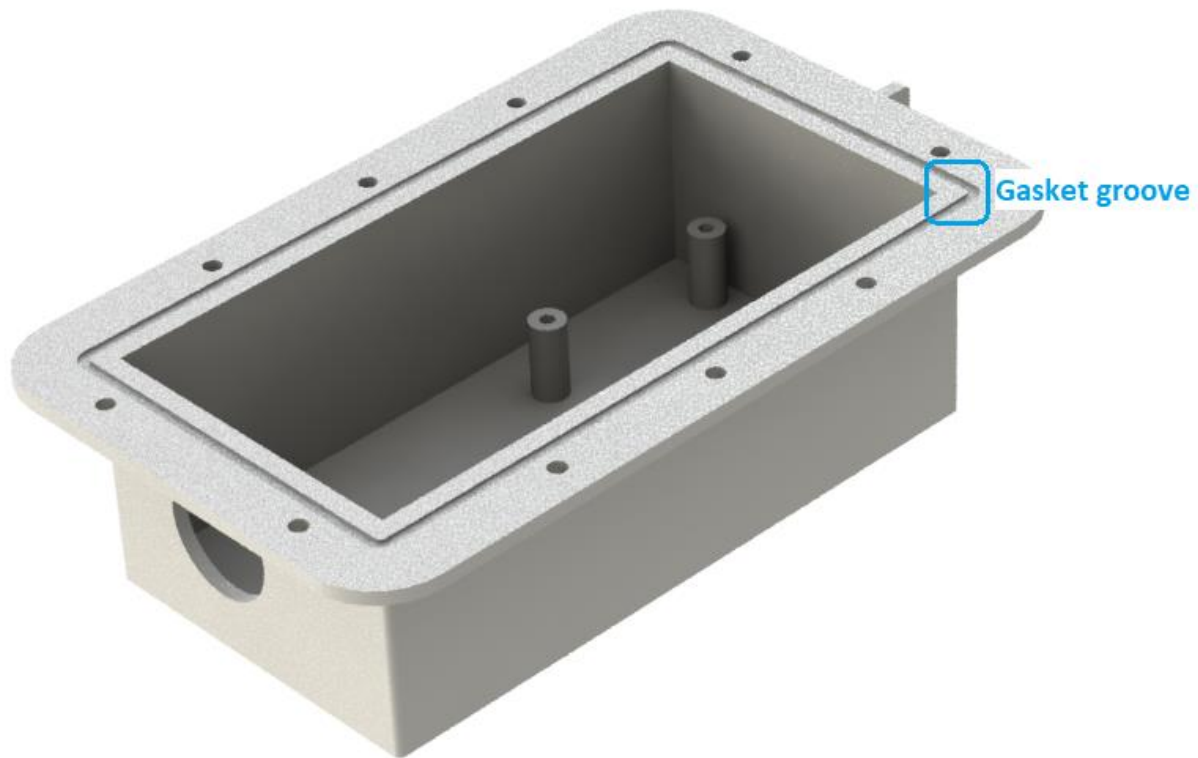
Figure 23. Gasket groove on the flange face of the bucket sensor casing

While the bolts of the flange face tighten, they compress the gasket which causes it fills the tiny spaces on the flanged surfaces and minimizes the risk of leakage. In this project, a gasket maker was used instead of the standard gaskets, because the casings were not built based on a regular standard shaping.

6.2   Software Components and System GUI

Unity game engine is used as a platform for data visualization, performance analysis, feedback registration and review, and post-feedback practice. The interface shown in Section 5.2.5 is designed inside Unity, as shown in Figures 19.

Figure 24 shows the main interface of the system for visualization playback (Figure 24a) and feedback registration (Figure 24b).

(a)
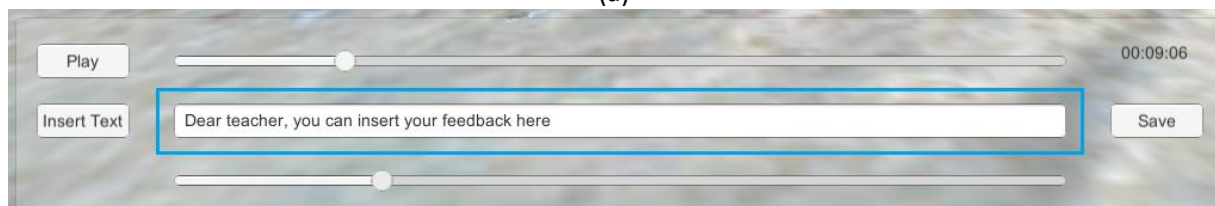
(b)

Figure 24. Developed GUI for (a) Visualization playback, (b) Feedback registration

Figure 25 shows a different instance of POA detection and presentation. Figure 25a shows the looking direction of the trainee in terms of a view cone. This is be used to automatically detect failure to do a shoulder check. Figure 25b illustrates an instance of bucket movement tracking. The magenta line is provided to enable instructors to assess the smoothness of the bucket movement. Figure 25c indicates a case where the trainee failed to move different axes simultaneously. The axes that were involved in the malpractice is highlighted using red spheres. Figure 25d depicts an instance of the bucket being too close to the superstructure of the excavator. This is marked using an orange cube around the bucket. Finally, Figure 25e illustrates the stability check. Depending on the pose of the excavator, the boundaries for the stable maneuver of the excavator are demarcated using an elliptic cylinder. When these boundaries are trespassed by the trainee, the color of ovoid changes, marking a potential hazardous maneuver.
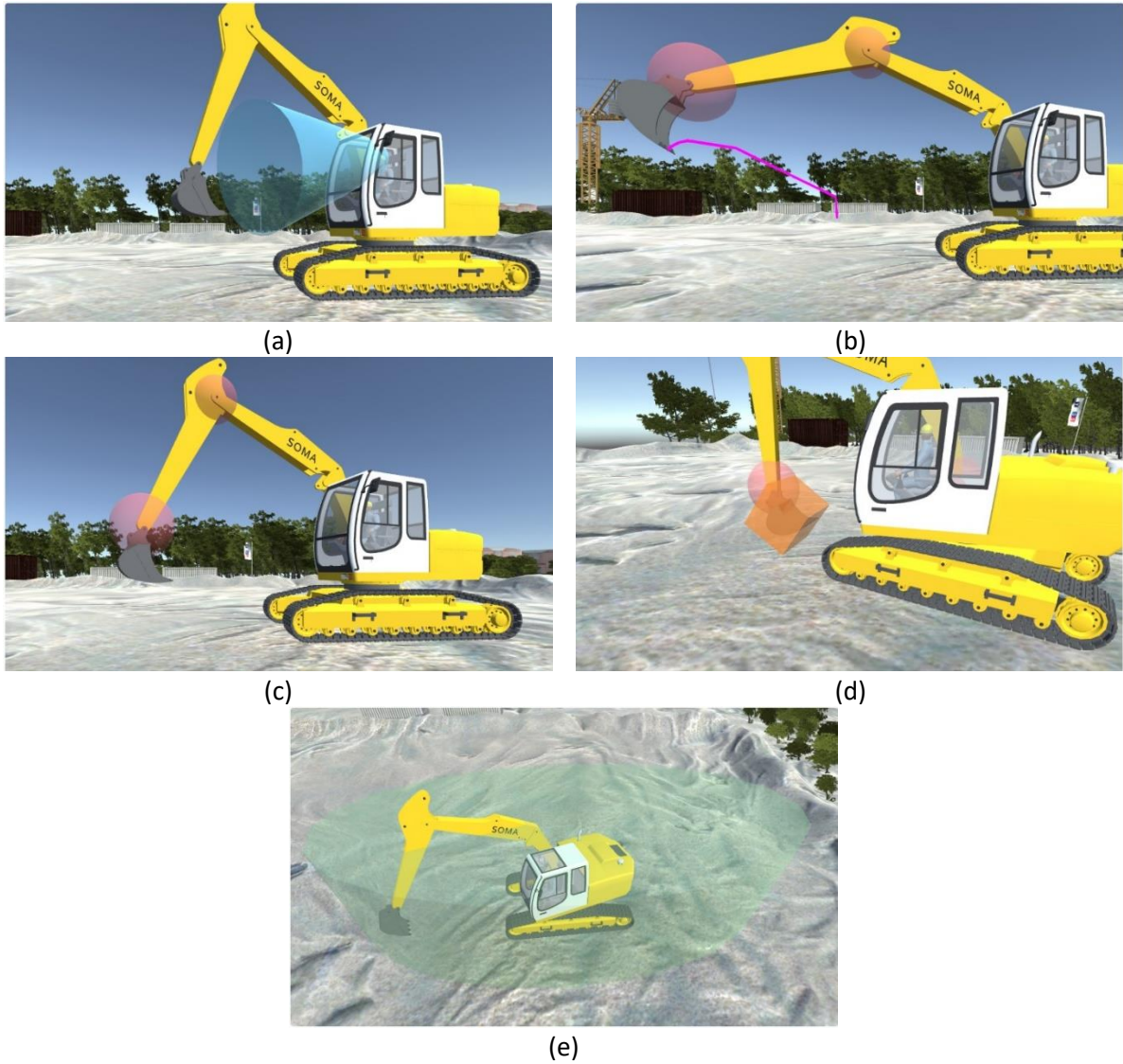
Figure 25. Developed GUI for (a) Shoulder check, (b) Bucket movement smoothness, (c) Simultaneous axes movement, (d) Bucket loading distance, (e) Stability check

Figure 26 shows the interface for feedback review by trainees. The figure illustrates how the feedback is rendered as a text and the reference to the visualization in the timeline which is specified with a blue marker.

Finally, Figure 27 presents the interfaces of post-feedback practice. As shown in this figure, trainees can use joysticks to take over control of the excavator in the same context. This feature can be used (1) by trainees to practice the task in the light of feedback provided by instructors, and (2) by instructors to demonstrate to trainees how certain maneuvers can be performed correctly.

Figure 26. GUI for feedback review
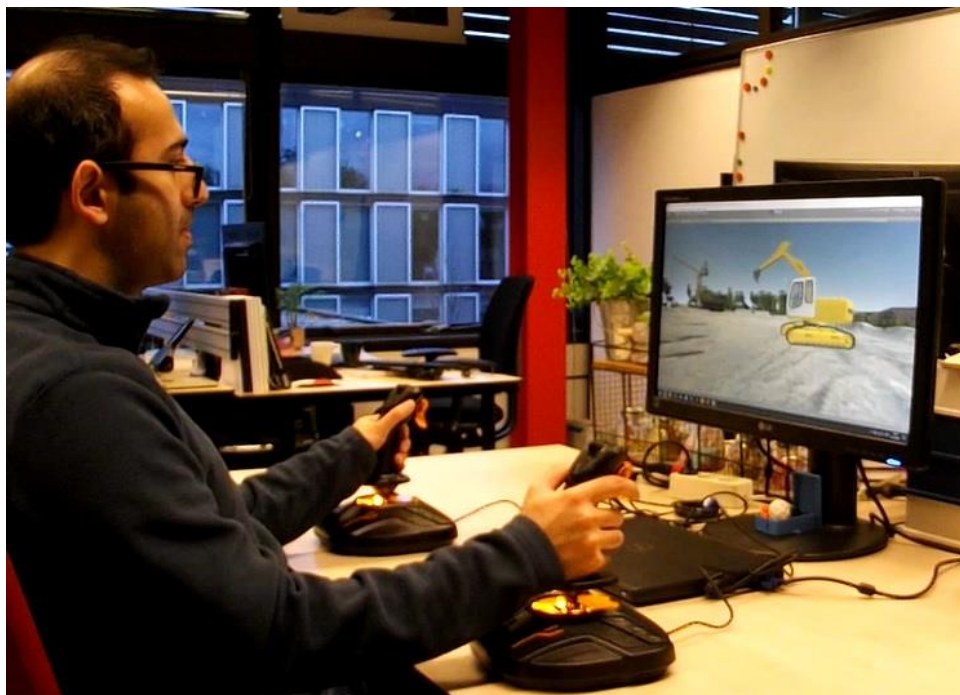
Figure 27. A trainee practicing in simulator mode

7 System Verification and Validation

Once the prototype is developed, it must be verified and validated. As explained in Chapter 2, verification is concerned with ensuring that the system meets the functional requirements of individual parts (i.e., modules). Validation, on the other hand, aims to assess the extent to which the system is able to deliver the high-level client requirements. This chapter reports on the verification and validation process of the system.

7.1 System Verification

To enable the verification of the system, it is important to check the functionality of each module separately. To facilitate this process, a small verification software tool was designed to check the sensor connectivity and stream of data in real-time. This means that neither the instructors or the trainees can see the GUI of the system while the excavator is operating. This software tool indicates the status of each sensor during the excavator operation, as shown in Figure 28. If any sensor is not working, the sensor name will be highlighted red, otherwise, the sensor name is shown in green. Also, the stream of data coming from the sensors is linked to a graphical model of excavator. This would allow a visual inspection of the data quality. If the data of certain sensors are missing or out of alignment, the tool allows quick identification.
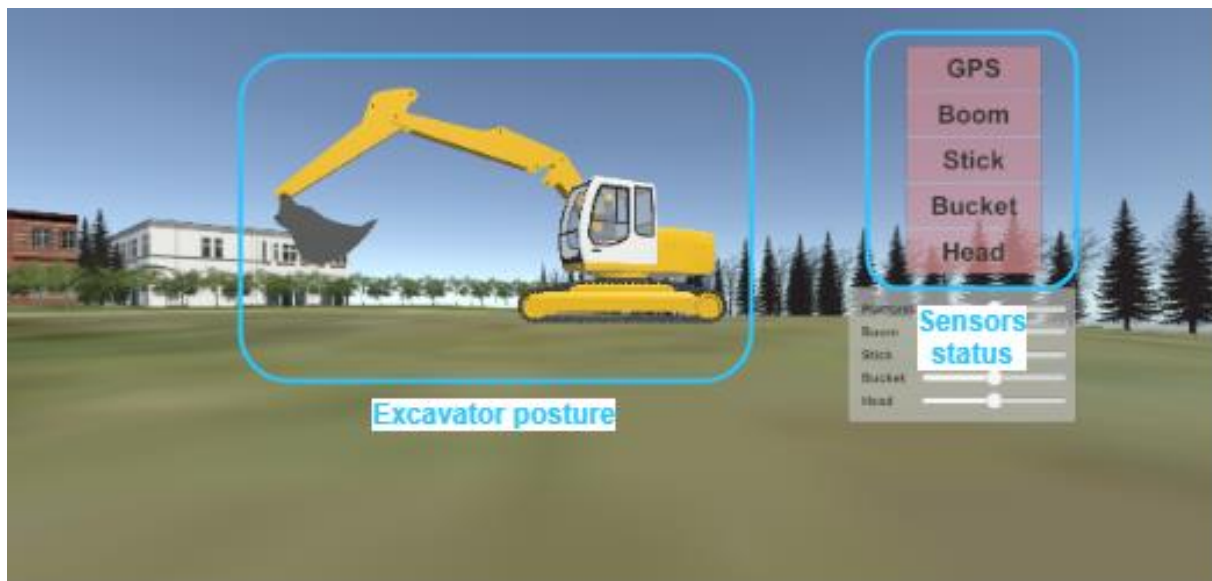
Figure 28. Real-time Viewer GUI

Using the above tool, the P.D.Eng. trainee ran 6 verification tests with the system, as shown in Figure 29. The first test was conducted on a toy excavator to check the feasibility of the solution without the interference of environmental noise. In the second test, the previously tested solution was implemented on a real excavator.
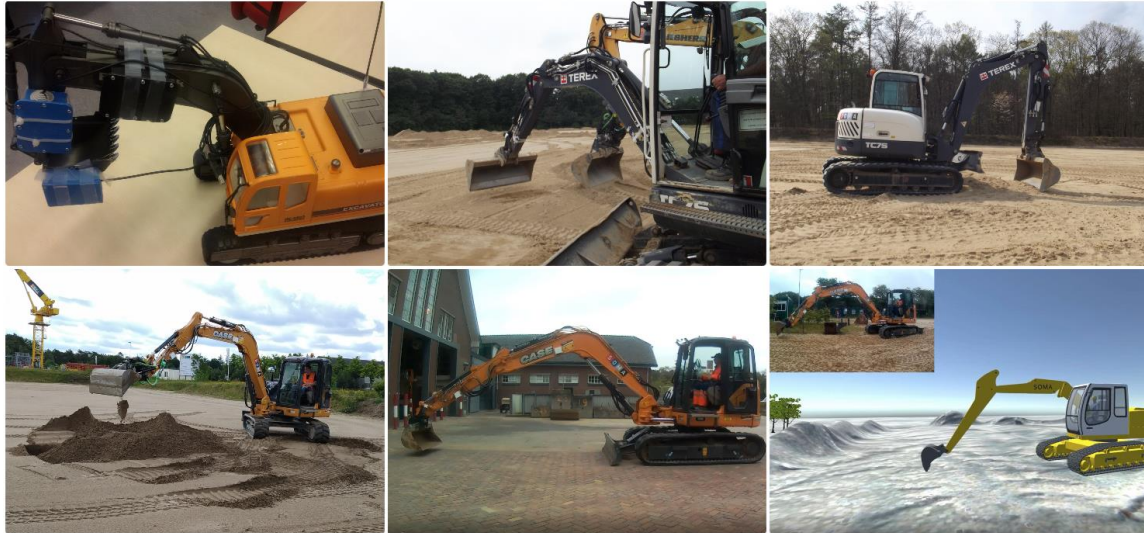
Figure 29. Six main test setups during the Feedback Support System development

The third and fourth tests focused on testing the head IMU and sensor casings. The fifth test focused on enhancing and debugging the software architecture and communication architecture of the system. In the last test, the accuracy of the visualization was tested. Based on the input from the last test, it became clear that the 3D model of the excavator needed to be aligned with the real excavator to improve the fidelity of the visualization. This necessitated a calibration process, which is explained in Appendix 3.

By the end of these verification tests, it became apparent that the modules are able to deliver their expected functionality. A final test was conducted in the SOMA college using the assembled system. It is verified that the system delivered the following functionalities:

1.   Motion capturing of excavator;
2.   Head tracking of the trainee;
3.   Accurate visualization;
4.   POA generation;
5.   Off-line visualization;
6.   Interactive and navigable GUI;
7.   Feedback annotation;
8.   Feedback review for trainees;
9.   Post-feedback practice.

The only functional requirement that was not met by the prototype was the representation of the surrounding equipment. This is mainly due to the logistical limitation with acquiring enough sensors to track more than one excavator simultaneously. Theoretically, the system supports the integration of data from several pieces of equipment in the visualizer, however, because of the above limitation, this function has not been tested.

7.2   System Validation

In the last phase of the project, the system was validated against the high-level requirements of the clients. As mentioned in Section 1.4, these requirements are:

1.   Usefulness
2.   User-friendliness
3.   Accuracy
4.   Reliability
5.   Robustness
6.   Affordability

Of the above validation criteria, accuracy and affordability were assessed quantitatively. Usefulness and user-friendliness were evaluated quantitatively through a workshop with instructors and students. Reliability and Robustness were qualitatively assessed through a set of experiments.

7.2.1   Usefulness and User-friendliness

To assess the usefulness and user-friendliness of the system, a workshop with instructors and trainees were organized, as shown in Figure 30.

Figure 30. Validation workshop at SOMA College

Instructors and trainees participated in the workshop and they rated different features of the system based on the provided evaluation form[1]. The evaluation of Feedback Support System is based on the metrics proposed by (Geissinger, 1997), (Escudeiro, Bidarra, & Escudeiro, 2006), and (Lê & Lê, 2007), which are mentioned in Table 7.

The evaluation form consists of seven generic metrics for both the instructors and the trainees. In addition to these seven items, three other metrics are specified for the instructors, and three other items are specified for the trainees.

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[1] The evaluation form is presented in Appendix 4.

Table 7. System validation metrics

Subject Target	Metric	Description
Generic	Visualization quality	The graphical quality of the elements exists in the Feedback Support System such as the scene, the excavator model, or POAs
	User-friendliness	The accessibility and usability of the elements in the Feedback Support System hardware and software interfaces regarding their location and their shape, e.g., the location of the timeline bar on the screen
	GUI guideline quality	The helpfulness of the guideline provided in the GUI for users
	User interaction level	The amount of user interaction in the GUI provided by the user controls, such as the pan, tilt, and zoom feature, or the playback speed control feature
	Tailorability	The flexibility of users to configure and customize the GUI based on their preferences
	Performance analysis usefulness	The usefulness of *Performance Analysis* function to guide instructors to view the most important parts of the trainee performance by generating POAs
	Real-video superimposition usefulness	The usefulness of adding a frame to show the real video of the trainee performance next to the performance visualization
Teacher Specific	System setup effort level	The amount of required effort to setup and configure the Feedback Support System
	Feedback registration quality	The ease of the instructor to insert text feedback via the GUI
	Versatility	The level of integration of the Feedback Support System to the current education system at SOMA College
Student Specific	Comfortability	The possibility to comfortably use the system during training or not
	Feedback review quality	The ease for the trainee to receive the text feedback
	Pedagogical aspects	The trainees' level of motivation and curiosity against their anxiety while using the system

The results of this workshop based on averaging the metric ratings are presented in Figure 31.
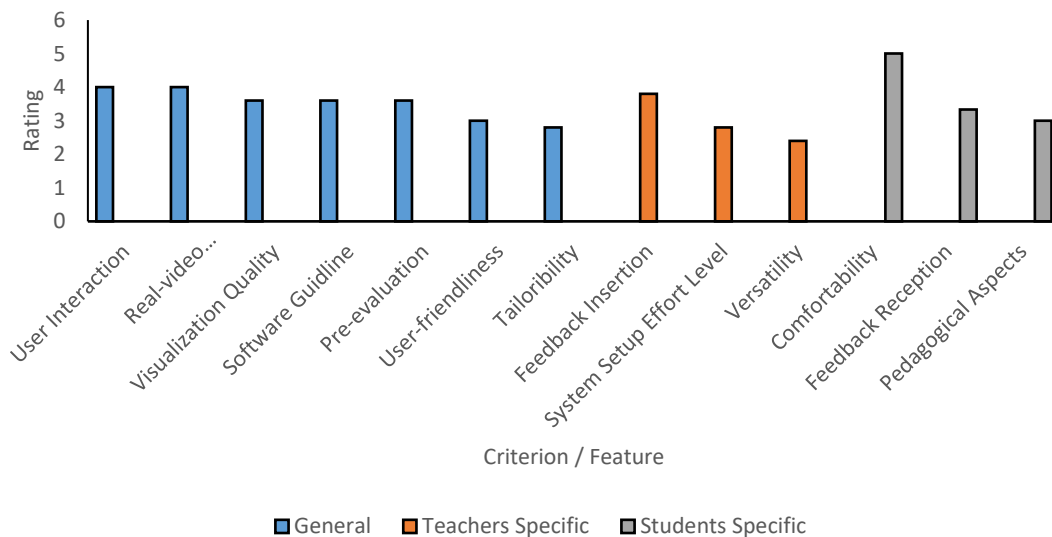

Figure 31. The Feedback Support System evaluation workshop result

From both instructors' perspective and trainees' perspective, *User Interaction* was the top-rated metric. The participants found the *Real-video Superimposition* feature very useful, because it reduces

the amount of miscommunication between the instructors and the trainees by looking at the real-video next to the visualization.

Further, the instructors found the *Feedback Registration* feature is a quite effective way to give textual feedback. *Versatility* got the lowest rating during the evaluation, because it was not clear for the instructors that how much return on investment they would obtain by using this system. They discuss about several recommendations that can help them to figure this out which is discussed in Chapter 11. The trainees believed that wearing the head IMU during the operation is comfortable. The trainees also agreed with the instructors that the text feedback can help them to improve their performance.

7.2.2 System Accuracy

After the fifth test, the instructors mentioned that the accuracy of the system in 3D visualization is not sufficient. So, the certain dimensions of an existing excavator (CASE CX80C) were measured and the size of the excavator 3D graphical model was adjusted. In the last test, the CASE CX80C excavator was used to check the accuracy improvement of the system based on its adjusted 3D model.

Generally, the visualization accuracy depends on the (1) hardware factor, and (2) software factor. The hardware factor means the effect of accuracy of the IMU sensors hired in this system, on the visualization. The hardware factor can be analyzed mathematically based on the kinematic chain of the excavator which is discussed in details in Appendix 6. The software factors means the effect of graphical model geometry employed in the system GUI, on the visualization. Based on the latter factor, the distance ratio among different joints of arm in the excavator graphical model should be equal to corresponding ratios in the real excavator.

7.2.3 System Reliability

During system implementation, an optimization was applied to the software architecture of the system for less energy consumption. In the fifth test setup, the energy consumption was measured which was 40% reduced compared to the previous architecture. This reduction in system energy rate enabled the system to continuously operate during on-equipment training sessions. To evaluate the system reliability regarding this optimization, a test was planned in which the Feedback Support System ran on one excavator during a real on-equipment training session at SOMA College for 3 hours. Afterward, the collected data from the test was visualized in which the system successfully covered the entire duration of the training session.

7.2.4 System Robustness

To test the robustness of the system, the sensors were mounted on an excavator during a real operation for one week. After this week, the sensors were tested again to ensure that sensors are not affected by the relatively long-term exposure to different weather conditions. It was confirmed by instructors that sensors were exposed to several heavy showers of rain during this period. The test indicated that sensors were not impacted and therefore it is concluded that the developed casings offer sufficient robustness for the system.

7.2.5 System Affordability
There are several solutions in market (see Section 9.1) that can capture the motion of an excavator same as the *Data Collection* module. However, the price of these solutions are not same as the Feedback Support System. According to the cost estimation performed in this project (see Appendix 5), the Feedback Support System is about 20 times less expensive than these solutions. Based on a

discussion with SOMA instructors, the Feedback Support System is considered as an affordable solution for SOMA College.

8 System Tutorial

A tutorial session was held at SOMA College for the instructors to introduce them what is the goal of the Feedback Support System, how it works, and how it can help them during their current educational program. The session started with explaining the definition of P.D.Eng. programs in the Netherlands, and how SOMA College and UT collaborated with each other during this P.D.Eng. project for delivering the Feedback Support System. The P.D.Eng. trainee in beginning also presented a progress summary of his project.

Afterward, the different hardware components of the Feedback Support System were introduced to the participants. The task of each component and how each component should be installed were explained. Meanwhile, the P.D.Eng trainee taught the instructors how to charge and how to maintain the system. Furthermore, a user manual (see Appendix 7) was also presented to guide instructors for step by step configuration of the system.

A practical demonstration of the system installation and testing was planned during the tutorial session. In this session, instructors installed the Feedback Support System on an excavator with the guidance of the P.D.Eng. trainee to get a hands-on experience with the system configuration. Then, one instructor operated the excavator for ten minutes for a demo data collection. The whole operation was recorded using an action camera installed on the excavator. The collected data and the recorded video were used later for the visualization playback and the feedback registration.

After the practical session, the procedure of transferring the collected data (synched data) to a computer is explained to instructors. The P.D.Eng. trainee introduced the features in the Feedback Support System GUI, and he taught them how they can work with the GUI. It was asked from all instructors to install the GUI beforehand. Then, instructors started working with the GUI (Figure 32) and they were able to ask for help from the P.D.Eng. trainee if they faced difficulties in interaction with the GUI.

Figure 32. Visualization playback of the practical session including the superimposed video recording of the action camera

The last part of the tutorial was a question and answer session in which instructors asked several questions about the next steps SOMA College should take to make this system ready to use. Regarding that, they also asked about development time and cost. In general according to the instructors' statement, this tutorial session provide them a better practical overview about the Feedback Support System which helped them to identify the added values of this system to the current educational system at SOMA College.

9 Solution Comparison and Impact

9.1 Solution Comparison

There are three companies in the world that manufacture measurement systems for construction equipment which are Topcon (Topcon), Leica (Leica), and Trimble (Trimble). However, none of these solutions are designed for educational purpose and they are generally used for precise earthmoving operation and insurance documentation. For instance, Topcon X63 is a system that helps excavator operators in real-time to precisely dig the ground, but instructors can use the system to evaluate the digging performance.

Industrial solutions such as Topcon X63 have some advantages, similarities, and disadvantages. I compare them below with the Feedback Support System and refer to it as an advantage if the market solution has more functionalities, and disadvantage if it has fewer.

Benefits of industrial solutions:

- Better accuracy. For instance, they can measure the position of the excavator bucket about 10 times more accurately than the developed system[1]
- Shock-proof. Most of them can resist shocks up to 100g. The Feedback Support System is not that rugged.
- No battery limitation of operation duration for these solutions. However, Feedback Support System can operate for a maximum of 4 hours after which it needs to be recharged.[2]
- Include terrain material models (e.g. soil or rock) that provide a better overview of the excavation scenario by visualizing the terrain behavior.

Similarities between industrial solutions and Feedback Support System:

- Require the same amount of configuration effort. All of them require a calibration process on each machine before being functional.
- Employ the GPS for positioning and the IMU modules for measuring equipment angles. So, none of them are dependent on construction equipment manufacturers.

Disadvantages of available industrial solutions:

- Are 20 times more expensive to produce than industrial solutions[3]
- Do not contain a head tracker to determine the operator's field of view inside the cabin.
- Do not contain an analysis engine for the pre-evaluation of operator performance.
- Are mostly wired, rather than wireless, making it more difficult to be installed on different types of equipment.

9.2 Solution Impact

The complete hardware and software solutions offer the first step toward plug-and-play solutions for machine tracking in operator education. How this is achieved, is elaborated below. By measuring, assessing and demonstrating the trainees' performance from different perspectives the instructor is able to provide substantial and specific feedback to the trainees without disturbing them (addressing the *continuity* issue). The instructor can safely approach any equipment in a virtual environment (*proximity* issue), and hence can evaluate trainees better by observing the operations with more

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[1] The proof is presented in Appendix 5.
[2] The user guideline is presented in Appendix 7.
[3] The cost estimation is presented in Appendix 6.

details. Furthermore, it is not necessary for the instructor to focus on several trainees at the same time during the outside training (*attention focus* issue). Therefore, he/she can concentrate on each trainee's performance one by one without overlooking any mistakes.

In addition, trainees can observe their performance post hoc, and view the instructor's feedback at the same time. This might improve their performance in the next on-equipment training session (*transience* issue). The process also solves misunderstandings between the instructor and the trainees (*perspective* issue). If there would be any misunderstanding, they can discuss it while watching the performance from the instructor's view (outsider perspective) and the trainee's view (insider perspective).
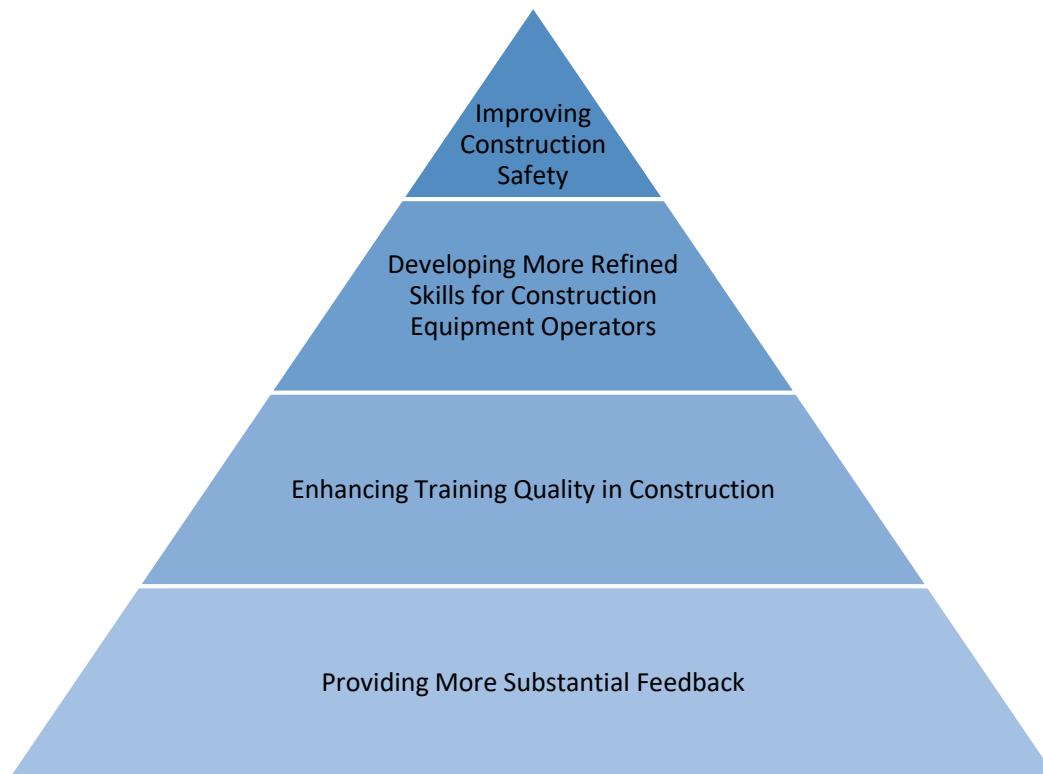
Figure 33. Feedback Support System social impact pyramid

In turn, the result of the project enhances the training quality of construction equipment operators. Through the use of this system, instructors can efficiently use their limited time during on-equipment training sessions to ensure that trainees are making a good progress. As shown in Figure 33, a better education by efficient instructions causes a faster development of more refined and ready-to-market skills for trainees. Trainees among this educational system rapidly acquire professional skills they need to work as construction equipment operators in the market. Ultimately, these operators with these skills can improve safety while working on construction sites.

Development of the Feedback Support System had practical impacts on the education system at SOMA College as well. The process of developing the system contributed to learning between the instructors and trainees themselves. The first workshop provided the opportunity for the instructors to discuss the criteria they used for evaluating trainees. To the best of the P.D.Eng. trainee's knowledge, such discussions were not very common in the regular work practice at SOMA. The discussions helped understand the logic behind each criterion and they tried to enhance their strategies for evaluation based on these logics. Workshops made knowledge more explicit and helped understand why instructors evaluate the trainee performance with certain strategies. During the second workshop, the

trainees also understood how instructors evaluate them. The common understanding between the instructors and the trainees is beneficial for the trainees because it helps them to acquire motor skills quickly and with better quality.

The Feedback Support System can be considered as a future solution for improving on-equipment and simulator training simulators. The system can actively capture the motion of different types of construction equipment in real on-equipment training sessions. The captured motion data can be analyzed later based on statistical and machine learning approaches to generate data-driven and agent-based models of the training session actors. These, thus, help to bridge a gap between equipment and simulator training. The main difference between the model extracted from the Feedback Support System and model extracted from other industrial solutions mentioned in the previous session is in the operator behavior modeling. Feedback Support System besides equipment motion tracks also the equipment operator. The equipment operator data can be used during the analysis to create more realistic models. By importing these models to the training simulators, the trainees can have a richer experience during the VR training.

10 Conclusion

The Feedback Support System is an affordable sensing kit that tracks both the equipment and the operator motions and provides an interactive interface for educational purposes. The system enables the instructors to closely observe the trainees' performance during on-equipment training sessions from different perspectives. This will reduce the chance of overlooking the trainees mistakes. The system also enables trainees to review their performance after the training session in a more comprehensive way, without forgetting instructors' feedback or losing focus due to interruptions.

SOMA College confirms that Feedback Support System has three added values to the current education system at SOMA College as follows:

1. The "*transience*" issue in the current fashion of giving feedback can be solved via using the Feedback Support System. By collecting trainees' performance, they always can payback their performance sequences without having the issue of recalling them;
2. The POA analysis feature of the Feedback Support System can be really useful to save the instructors' time for evaluating the trainees. During on-equipment training, trainees may be idle for plenty of time (e.g., break times). The POA analyzer can provide hinds to instructors to skip these periods;
3. The *head tracker* can provide information about the trainees' situational awareness.

On the other hand, SOMA College believes that Feedback Support System has three main drawbacks as follows:

1. The accuracy of the visualization in the current state is not enough to analyze the quality of the trainees' performance. The accuracy is interpreted as (1) the accuracy with which the trajectory of the bucket's tip is traced, as discussed in details in Appendix 5, and (2) visualization lag (frame rate drop) in rendering fast maneuvers;
2. The system is only implemented on one excavator type and does not yet offer functionality for other types. This requires calibration;
3. Real-video recordings are not integrated with the Feedback Support System yet which makes it difficult to synchronize the video with the visualization.

The current state of the Feedback Support System prototype could be assessed by SOMA, for example by using an assessment framework to facilitate their decision about the use of it in their training. This also requires them to estimate the amount of cost and time needed to complete the prototype to a market-ready product.

11 Future Work

Several improvements can be applied to the current prototype to convert it to a high-fidelity prototype in the short-term. These improvements target enhancing visualization features, VR features, and configurability of the system. Additionally, several recommendations are presented that can be considered as potential research and development lines in the long-term for industrializing the system.

11.1 Improvements

- Another IMU can be added to the track platform of the excavator for realistic visualization of the excavator. Moreover, the IMU can be used to measure the vibration of the platform as an operator performance indicator.
- A state identification engine can be merged to the POA analyzer to enhance the performance analysis accuracy. This engine would be able to automatically detect the state of the excavator (e.g., swinging, digging, etc.) and use this information to better analyze the performances of trainees. To put this in perspective, it can be the case that certain maneuvers are acceptable during a swing while not acceptable during a dig. State identification can help analyze state-dependent POAs.
- The 3D model of the excavator can be parameterized. In the parametric model, the user can adjust the model via a GUI. In this way, the feedback support system can be used for different excavators of different sizes.
- A report can be generated about the user performance during the post-feedback practicing when the practicing is finished.
- A power distributor can be installed on the excavator to charge the sensors on spot. Otherwise, all the sensors should be dismounted from the equipment every time for charging.

11.2 Recommendations

- Instead of the IMUs, the linear encoder[1] data from the excavator manufacturer can be used. The encoder data is less noisy, it is calibrated, and it has better accuracy in different postures of the excavator.
- The head tracker can be replaced by an eye-tracker glass for better accuracy and also determining the concentration point of the operator.
- It would be worthwhile if a soil model is added to the Feedback Support System GUI.
- The stability of the excavator during digging can be determined by using a load cell on the bucket to measure the loaded weight. Later, the stability can be visualized during the playback as another operator performance indicator.
- There can be a user interface on the excavator cabin which can be used by the operator to insert his/her name. So, the data logging process can be done automatically and the data can be transferred directly to a main sever rather than a USB stick memory. In other words, this would eliminate the need to manually transfer the data to the server using USB stick.
- It is highly recommended that the single-board computers be replaced with industrial embedded computers.

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[1] Hydraulic cylinders of an excavator are usually equipped with a linear position measuring sensor called *linear encoder* which is used in the feedback loop of hydraulic pump controllers.

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Appendix 1: Smoothness Measurement

The smoothness of an object movement can be evaluated based on different metrics (Balasubramanian, Melendez-Calderon, Roby-Brami, & Burdet, 2015). In Feedback Support System three different metrics are used to have a better indication about the smooth movement of the excavator bucket. These 3 metrics are as follows:

1. Root mean square of bucket jerk;
2. Number peaks in bucket jerk;
3. Log dimensionless bucket jerk.

These metrics are computationally effective which can be also used during real-time evaluation of the operator performance in *simulator mode*.

The jerk of the bucket $\vec{j}$ is computed based on the 3rd derivation of bucket displacement $\vec{r}$ (in the inertial coordinate system) with respect to the time as expressed in Equation 1:

Equation 1

$$\vec{j} = \frac{d^3\vec{r}}{dt^3}$$

For all of the mentioned metrics, a series of bucket jerk is required. To achieve that, the jerk of the bucket is computed during a one second time window containing 200 samples.

1- Root mean square (RMS) of bucket jerk:

The RMS of the bucket jerk is computed according to Equation 2:

Equation 2

$$j_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}|\vec{j_i}|^2}$$

in which n is equal to 200.

2- Number peaks (NP) in bucket jerk:

The number peaks in the jerk series is computed according to Equation 3:

Equation 3

$$NP = \left|\left\{\left(\frac{d\vec{r}}{dt}\right) \ s.t. \ \frac{d^2\vec{r}}{dt^2} = 0 \ and \ \frac{d^3r}{dt^3} < 0\right\}\right|$$

in which |.| represents the cardinality of the set.

3- Log dimensionless bucket jerk (LDLJ):

The Equation 4 is used to measure the log dimensionless bucket jerk:

Equation 4

$$LDLJ = \log\frac{(t_n - t_1)^5}{v_{peak}^2}\int_{t_1}^{t_n}|\vec{j}|^2 dt$$

in which n is equal to 200 and v_{peak} is computed from Equation 5:

Equation 5

$$v_{peak} = max\left\{\frac{d\vec{r_i}}{dt}\right\} \quad i = 1, ..., n$$

To have an overview about the smoothness of the bucket movement, all of these three calculated values are compared with three specific thresholds respectively. If at least two of these values be greater than their corresponding thresholds, the movement would be labeled as "jerky".

Appendix 2: Prioritization Form

Table 8. Pre-evaluation metrics prioritization form used in the 1st workshop

| Metric | Target Skill | Description | Requirements | | Feasible in P.D.Eng. Yes: In Scope No: Out of Scope | Priority (1 to 5) 1: Not Useful 2: Partially Useful 3: Useful 4: Very Useful 5: Crucial |
			Technology	Effort Low ~ Days Medium ~ Weeks High ~ Months Very High ~ Years		
Shoulder Check	Situational Awareness	Detecting the attention point of the operator in the cabin while he/she is moving the excavator backward. In this situation, the operator should look back while moving the excavator in that direction, otherwise the maneuver would be unsafe.	Machine Vision Tracker / Inertial Measurement Unit / Infrared Tracker / Magnetic Tracker	Medium	Yes	
Operator Concertation Point	Situational Awareness	While performing a swing action on an excavator, the operator should focus on the bucket destination rather than following the bucket itself.	Machine Vision Tracker + Eye Tracker	High	No	
Scenario Evaluation	Overall Performance	Checking that the operator finishes the defined scenario successfully or not.	Scenario Management Software Interface + LiDAR Scanner	Very High	No	
Simultaneous Axes Movement	Excavation Performance	Counting how many excavator joints can the operator move at the same time.	Inertial Measurement Unit	Low	Yes	

Bucket Movement Smoothness	Excavation Performance	How smoothly the operator moves the bucket of the excavator.	Inertial Measurement Unit	Medium	Yes	
Bucket Load	Productivity	Measuring the amount of soil the operator has moved during the operation.	Load Sensor / LiDAR Scanner	High	No	
Trench Geometry	Excavation Performance	How the operator digs a trench.	LiDAR Scanner	Very High	No	
Operator Drowsiness Level	Situational Awareness	Measuring the alertness level of the operator while working with the excavator.	Angelo meter and/or Thermal Camera	Very High	No	
Operator Stress Level	Confidence	Computing the stress level of the operator during operation based on his/her physiological signals.	Conductive Tactile Sensor	High	No	
Axes Movement Speed	Excavation Performance	How fast the operator moves the different joints of the excavator.	Inertial Measurement Unit	Low	Yes	

Appendix 3: System Calibration

IMU sensors have a measurement reference that may are not essentially aligned with ground level. The misalignment causes a measurement offset between arm component (e.g., boom) and their corresponding IMUs (e.g., boom IMU) as shown in the Figure 34.

Figure 34. Inclinations of the excavator boom and the boom IMU

In this case, the measured angle of the IMU is not equal to the angle between the boom and the ground. So, there can be always an offset between the real angle and the measured angle. The process of computing the amount of this offset is called calibration.

Therefore, an angle meter (Figure 35) is used to calibrate the Feedback Support System IMUs.

Figure 35. A digital angle meter

The meter was placed separately on the boom, the stick and the bucket of the excavator to measure the exact angle between of each part and the ground level respectively. The difference between the angle meter measurement and the corresponding sensor measurement is considered as the offset. There are three offsets for the system: the boom offset, the stick offset, and the bucket offset. These offsets should be manually inserted to the Unity game engine configuration.

Appendix 4: Usefulness and User-friendliness Evaluation Form

The evaluation form of Feedback Support System is present in Table 9.

Table 9. The second workshop form to evaluate Feedback Support System

Criterion / Feature	Description	Rating (1 ~ 6) 1:Very Poor ~ 6: Excellent
Visualization Quality	The graphical quality of the elements exist in the Feedback Support System software such as the scene, the excavator model, visual indicators, etc.	
User-friendliness	The accessibility and usability of the elements in the Feedback Support System hardware and software regarding their location and their shape, for instance the location of the timeline bar in the screen.	
Software Application Guideline	How much the guideline provided in the software clear for the user.	
User Interaction	The amount of user interaction in the software provided by the user controls, such as the pan, tilt, and zoom feature or the playback speed control feature.	
Tailorability	The flexibility of the user to configure and customize the software based on his/her preferences.	
Pre-evaluation Feature	The accuracy of the *Pre-evaluation* feature to guide the user to view the most important timespans of the recorded trainee performance.	
Real-video Superimposition Feature	The feature of adding a frame to show the real video of the trainee performance next to the virtual performance visualization.	
Instructors only		
System Setup Effort Level	The amount of required effort to setup and configure Feedback Support System.	
Feedback Insertion	How easy for the instructor to insert a text feedback for the trainee via the software.	
Versatility	The level of integration of Feedback Support System to the current education system at SOMA College.	
Trainee only		
Comfortability	Is it comfortable for the trainee to use the system during his/her training or not; e.g. wearing the *Head Tracker*.	
Feedback Reception	How easy for the trainee to view a text feedback of the instructor via the software.	
Pedagogical Aspects	The trainee is feeling more motivated and curious while using the system or he/she is feeling more anxious and nervous while using it.	

Appendix 5: System Accuracy

One metric to determine the system accuracy is to compute the accuracy of localizing the bucket tip via the system in a 2D plane (Topcon, 2013).
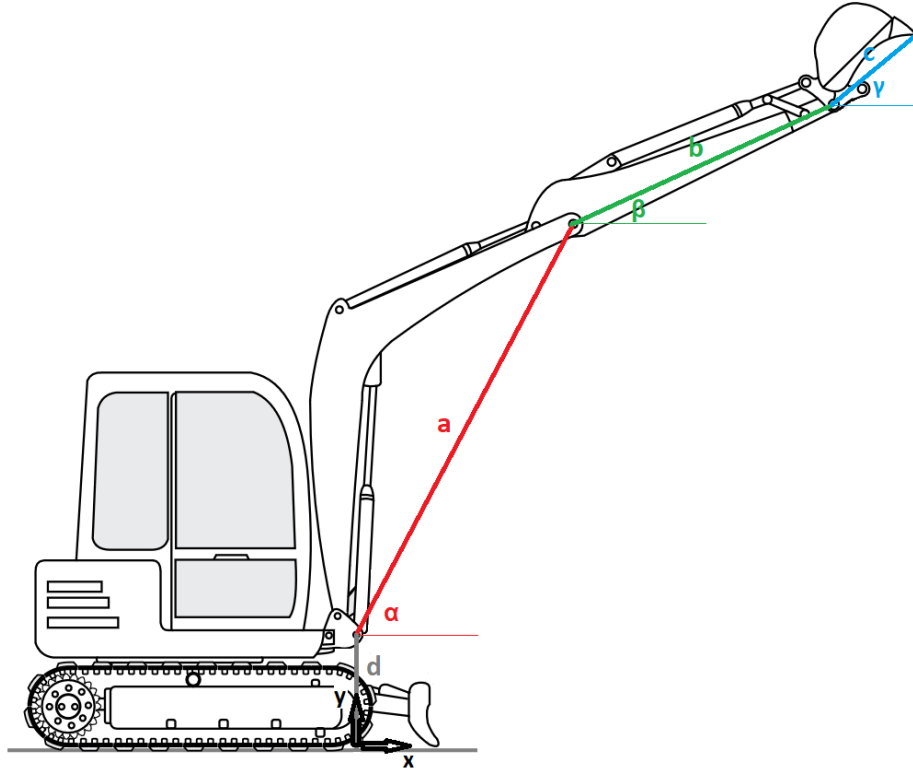

Figure 36. Excavator bucket tip kinematic chain

Based on Figure 36 the position of the bucket tip $\hat{\vec{r}}$ in the excavator local coordinate system can be computed from Equation 6:

Equation 6

$$\hat{\vec{r}} = ae^{i\alpha} + be^{i\beta} + ce^{i\gamma} + di$$

in which a is the boom effective length, b is the stick effective length, c is the bucket effective length, d is the ground clearance, α is the boom absolute rotation, β is the stick absolute rotation, and the γ is the bucket absolute rotation. The position of the bucket tip based on the Feedback Support System computation is based on Equation 7:

Equation 7

$$\vec{r} = (a + \delta)e^{i(\alpha+\varepsilon)} + (b + \delta)e^{i(\beta+\varepsilon)} + (c + \delta)e^{i(\gamma+\varepsilon)} + (d + \delta)i$$

in which δ is the length measurement error and ε is the angle measurement error. It is assumed that the calibration error, the sensor mounting offset error, and synchronization side effect error are neglectable. Moreover, for simplification it is assumed that the bucket sensor is mounted on the bucket itself rather than its backbone. The localization error can be computed form Equation 8:

Equation 8

$$E = \left\| \vec{r} - \hat{\vec{r}} \right\|_\infty = \max\{x - \hat{x}, y - \hat{y}\} = y - \hat{y}$$

which is equal to the bucket horizontal error. The horizontal error is greater than the vertical error because it is affected by the ground clearance measurement error. By the assumptions below:

$$\begin{cases} \sin \varepsilon \approx \varepsilon \\ \cos \varepsilon \approx \varepsilon \\ \delta \varepsilon \approx 0 \end{cases}$$

Equation 8 can be simplified to Equation 9:

Equation 9

$$E(\alpha, \beta, \gamma) \approx \delta(\sin \alpha + \sin \beta + \sin \gamma) + \varepsilon(a \cos \alpha + b \cos \beta + c \cos \gamma)$$

It can be understood from Equation 9 that the error varies with different values of the boom, the stick, and the bucket absolute rotations. The extremum point of the error function can be found from Equation 10:

Equation 10

$$\nabla E(\alpha, \beta, \gamma) = \vec{0}$$

which leads to three equations:

$$\begin{cases} \dfrac{\partial E}{\partial \alpha} = \delta \cos \alpha - \varepsilon a \sin \alpha = 0 \\ \dfrac{\partial E}{\partial \beta} = \delta \cos \beta - \varepsilon b \sin \beta = 0 \\ \dfrac{\partial E}{\partial \gamma} = \delta \cos \gamma - \varepsilon c \sin \gamma = 0 \end{cases}$$

From the equation system above, the critical values for the absolute rotation can be determined which are:

$$\begin{cases} \alpha_c = \tan^{-1}(\dfrac{\delta}{\varepsilon a}) \\ \beta_c = \tan^{-1}(\dfrac{\delta}{\varepsilon b}) \\ \gamma_c = \tan^{-1}(\dfrac{\delta}{\varepsilon c}) \end{cases}$$

Finally the maximum error can be computed from Equation 11:

Equation 11

$$E_{max} = E(\alpha_c, \beta_c, \gamma_c)$$

The system maximum error depends on the equipment arm dimensions.

The maximum error is computed for CASE CX80C excavator as an example ($a = 3.51\, m$; $b = 2.21\, m$; $c = 0.78\, m$; $\delta = 0.01\, m$; $\varepsilon = 2°$)[1]:

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[1] In this case Xsens sensors are used which have 1 degree of drifting error per hour (Xsens, 2015). So, the ε will be increased each hour by one degree. But, it is assumed that the measurement won't last for more than an hour.

$$\begin{cases} \alpha_c = \tan^{-1}\left(\dfrac{\delta}{\varepsilon a}\right) = 4.64° \,, 184.64° \\[2mm] \beta_c = \tan^{-1}\left(\dfrac{\delta}{\varepsilon b}\right) = 7.35° \,, 187.35° \\[2mm] \gamma_c = \tan^{-1}\left(\dfrac{\delta}{\varepsilon c}\right) = 20.06° \,, 200.06° \end{cases}$$

The inverse tangent function has two output values in which because of the CASE CX80C geometry (CASE, 2019), only the following values are valid:

$$\begin{cases} \alpha_c = 4.64° \\ \beta_c = 7.35° \\ \gamma_c = 20.06° \end{cases}$$

Therefore, the maximum error in this case would be:

$$E_{max} = E(\alpha_c, \beta_c, \gamma_c) = 24.3 \; cm$$

However, the Topcon X63 system has the accuracy of 3.05 cm (Topcon, 2013).

Appendix 6: Hardware Specifications and Cost Estimation

The hardware components specifications of *motion capture module* and the hardware components cost estimation is presented in Table 10.

Table 10. Feedback Support System hardware specifications and cost estimation

Central station		Price (€)
Single-board Computer	Raspberry Pi 3 B	35
Memory Card	Kingston Micro SD 16GB	7
Wi-Fi Router	GL-AR300M-Ext	46
Rubber Ducky Antenna	2 x Joy-it BananaPi-ANT5DB	12
GPS sensor	u-blox EVK-M8T	225
Power Supply	Xiaomi Mi Powerbank Li-ion 20000 mAh PLM06ZM	33
Boom sensor		**Price (€)**
IMU	MTi-3-8A7G6-DK (discontinued)	388
Single-board Computer	Raspberry Pi 3 B	35
Memory Card	Kingston Micro SD 16GB	7
Power Supply	König Powerbank 5000 mAh	14
Stick sensor		**Price (€)**
IMU	MTi-3-8A7G6-DK (discontinued)	388
Single-board Computer	Raspberry Pi 3 B	35
Memory Card	Kingston Micro SD 16GB	7
Connection Cable	Sommer Cable 540-0051	1
Cable Gland	Spiral Gland PG9	2
Cable Connector	Weipu SP2110 / S4II	7
Power Supply	König Powerbank 5000 mAh	14
Bucket sensor		**Price (€)**
IMU	MTi-3-8A7G6-DK (discontinued)	388
Connection Cable	Sommer Cable 540-0051	1
Cable Gland	Spiral Gland PG9	2
Cable Connector	Weipu SP2111 / P4II	7
Head tracker		**Price (€)**
IMU	WitMotion BWT61CL	41

Appendix 7: User Guideline

Follow the steps below to install the hardware part of Feedback Support System successfully:

1. Charge all the hardware components (the *central station*, the *boom sensor*, the *stick sensor* and the *head tracker*) before the installation using any kind of USB charger.
2. Mount the *central station* in the excavator cabin in the way that the Wi-Fi antennas stay vertical as shown in Figure 37.

Figure 37. Central station mounted in the excavator cabin

3. Mount the GPS antenna outside the cabin for a better GPS signal strength.
4. Install the *boom sensor*, the *stick sensor*, and the *bucket sensor* based on the arrangement presented in Figure 38 using bolts and spring washers.

> Spring washers are useful to keep the bolts tighten in the situation that the bolts are tolerating lots of machine vibrations.

Figure 38. Sensor arrangement on an excavator

5. Always be sure that the sensors installed in the way that they are perpendicular to the ground. You can use the spirit levels installed on the casings (Figure 39) to check that.

Figure 39. Bucket sensor equipped with a spirit level on its casing

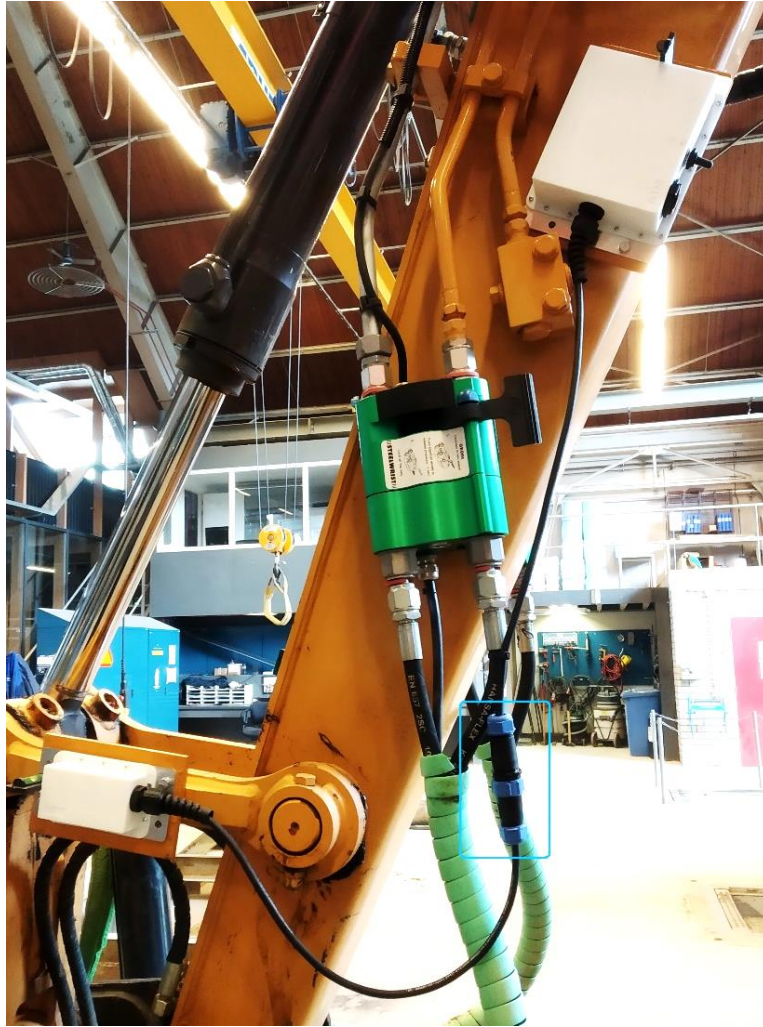6. Connect the *bucket sensor* cable to the *stick sensor* connector as shown in Figure 40:

Figure 40. Bucket sensor and stick sensor connection

7. Ask the operator to wear the *head tracker* cap.
8. Insert the USB stick to the *central station* USB slot.
9. Turn on the *central station*. Be aware that there are two power switches for the *central station*. First turn on the *Wi-Fi power switch*, then wait for **2 minutes** and finally turn on the *data logger power switch* (Figure 41).

> ⚠️ Never turn on the *central station* while the Wi-Fi external antennas and/or the GPS antenna are detached.

Figure 41. Central station view

10. Turn on the *head tracker* above the cap. If the tracker is fine, its blue light should start blinking. As the *central station* connects to it, the light should be fixed.
11. Turn on the *boom sensor* and the *stick sensor*. Then the system is ready for the software configuration.
12. After data collection, turn off all the hardware components, pull out the USB stick and connect it to the computer running *Feedback Support System Player.*
13. Copy the collected data (with **CSV** file format) from the USB stick to the *Feedback Support System Player* data folder and rename the filename to the trainee's name.
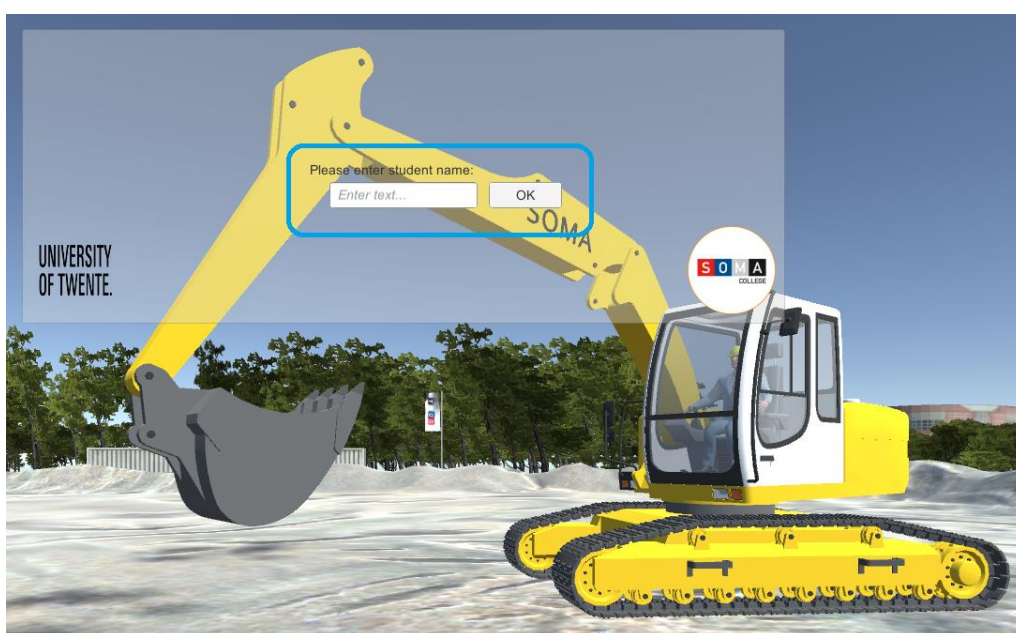14. Open *Feedback Support System Player* and type the trainee's name into the text box demonstrated in Figure 42.

Figure 42. Feedback Support System Player graphical user interface

15. By pressing OK, the player loads the log file. Now can play the motion data visualization.
16. To view the application guideline press **F1** key on the computer.