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Making the Invisible Visible for Off-Highway Machinery by Conveying Extended Reality Technologies

Deliverable 6.1 – Integrated THEIA-XR technologies and methodologies and use case implementation (first version)

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Author(s)	Manuel Kulzer (HDM), Markku Pusenius (CREA), Thomas Howard (HAP), Anastasia Sergeeva (UL), Pekka Yli-Paunu (KAL), Laura Makinen (KAL), Volker Waurich (TUD), Sebastian Lorenz (TUD), Kaj Helin (VTT), Andrea Alesani (VTT), Thomas Kernbauer (TUG)
Contact details of the coordinator	Martijn Rooker, martijn.rooker@tttech.com
Internal Reviewer	Daniel Roeck, PRIN Pekka Yli-Paunu, KAL

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Executive summary

This deliverable describes the integration activities performed so far within the three use cases. Although technology development is still in full progress in the work packages 3 till 5, first prototypes are available which are going to be tested and validated within the real-life demonstrators and in the real dedicated environments. To perform the tests, these first versions of the prototypes will be either integrated in the real demonstrators or potentially first lab demonstrators, to later be transferred to the real machines.

This document is meant to provide details about the integration activities, including the different infrastructures available at the mobile machinery (i.e., snow groomer, reach stacker and excavator) and how the first prototypes are integrated or will be integrated in the infrastructures of the machines. Many of the technologies are standalone, but the aim is at the end of the project to have most of them fully integrated into the machinery to aid the human operators.

Each section highlights the different technologies and their status for integration. Certain technologies can already be integrated on the actual machines, whereas some of them are still in a lab stage and will be integrated in the second phase of the project. Additionally, each section will highlight the next steps in the integration process for the dedicated use case. This deliverable will be the basis for the further work to be performed in Work Package 6, which will focus on testing, demonstration and validation of the individual methodologies and technologies.

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1 Introduction

This deliverable D6.1 summarizes the work that has been performed in the first cycle of Task 6.1, related to the individual developed components and methodologies, and their interfaces in the 3 dedicated use cases of THEIA^{XR}.

The aim of Task 6.1 is to implement and integrate the applications and technologies coming from the technical work packages WP3 – WP5, into the use cases. The first integration steps that will be done here are either modifying the applications and technologies to fit the actual demonstrators (i.e., the snow groomer, reach stacker or the excavator) or potentially deploying the solutions with simulated environments and potentially using simulated data. The actual demonstration of the solutions with the use cases and the real environments will be performed in Task 6.2 and the evaluation of the technologies is done in Task 6.3.

The work package 6 brings all the work from the other work packages together, but also provides feedback to all the other (technical) work packages (as can be seen in Figure 1). The use cases are specified in work package 2, which also defines the (technical) requirements for the technologies being developed in work packages 3-5. These work packages provide the technologies and methodologies that will finally be integrated into the demonstrators, which is happening in work package 6. Additionally, the results coming from work package 6 flow back into the technical work packages and into the specifications, resulting in the final use case description and improved technologies.

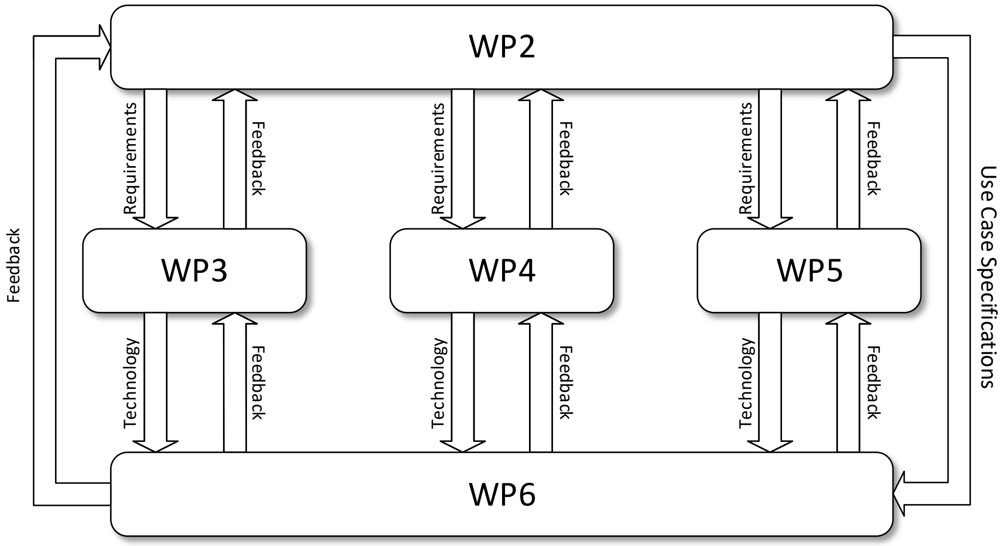


Figure 1: Work Package interaction within THEIA^{XR}

Deliverable D6.1 will therefore provide the first version of a subset of integrated solutions and applied methodologies and the first releases of the technologies coming from WP3-WP5, based on the requirements and specifications defined in WP2. Additionally, it will provide the first implementations of the use case applications and services.

In the following chapter, the three different use cases are considered separately, highlighting the actual infrastructure, the technologies integrated and the upcoming work to be performed for the specific use case that is being discussed, which is discussed in section 2.1 (use case 1), 2.2 (use case 2) and 2.3 (use case 3). Finally, the deliverable is concluded in chapter 3.

2 Use Case Implementation

In the following three subsections, the use cases (Snow grooming, logistics and construction) will be described. It will start with an overview of the infrastructure that is being used within the mobile machines (snow groomer, reach stacker and excavator). Afterwards, the current step of integration of the different methodologies and technologies will be described. Each subsection will finalize with a description of the next steps on the integration phase.

2.1 Use Case 1 – Snow grooming

2.1.1 UC1 Infrastructure

For the snow groomer use case there is a state-of-the-art snow groomer available, furthermore a fully equipped operator cabin is provided.

Depending on the time of implementation and availability, the demonstrator snow groomer may not always be the same, but the research content will be transferred. A ski area or cross-country skiing centre in the vicinity of Sterzing, Italy is selected for integration in the real environment. The target area will be selected from case to case. For each real-world location used for the integration, it is ensured that a summer scan of the terrain exists and therefore an accurate digital terrain model is available (see Figure 2). In addition, there is a target geometry defined.

Figure 2: Digital terrain model with target surface of cross-country trails

The snow groomer itself is equipped with a telematic box to track vehicle data and an accurate snow measurement system, based on GNSS with RTK to track the exact localization and orientation of the vehicle. It is possible to retrieve data via CAN.

Prototype technologies are set up in a real environment to test the functionality in what can be extreme conditions. For this purpose, the functionality and control of these will take place via a separate laptop and will not yet be fully integrated into the snow groomer. In the first phase, the focus lies on prototypes that are exposed to weather conditions and installed outdoor.

Later, haptic feedback systems will also be integrated into the original hardware wherever possible, to provide the best possible comparison with the original controls. Visual display options in the snow groomers driver’s cabin will also be integrated at a later moment.

To be closest to reality, the operator cabin as a standalone demonstrator is an original Leitwolf cabin. The operator can use a centre-seat and there are also two additional seats installed to support the testing and giving space to the test instructor. The HMI is arranged, adjustable and usable like in the real machine. To ease transport and logistics, the cabin is packed on a steel structure and can be moved with a crane or forklift.

2.1.2 Integrated Technologies/Methodologies

2.1.2.1 Application of Co-Design Methodology in UC1

Following the user research conducted in Sterzing, Italy, as part of T3.1 (see Figure 3), a problem scenario was defined (first step of the scenario-based design approach), describing a current typical snow-grooming operation. This scenario was shared with the consortium. On October 19, 2023, an ideation workshop was held involving all active partners in this use-case. In this workshop, ideas for technology usage and some concepts already in development were collected and discussed in terms of their technical feasibility and expected utility for the operators. It was assumed that operators may have difficulties coming up with technology usage and interaction ideas on their own and may both over- and underestimate what is currently technically possible. Thus, the input from project partners was going to be implemented into a first activity scenario version, providing examples of how XR technology could realistically support operators at work and serving as a basis for the idea generation and validation with operators.

The activity scenarios, as defined in [1], were internally dubbed “vision scenarios” to highlight their purpose as ideal interaction concepts, outlining the goals of development. During the internal review of the initial UC1 ideation workshop’s results, the current spectrum of ideas was found to be rather realism-cantered, focusing on mostly feasible solutions. To include some more visionary, speculative ideas as well, it was considered necessary to create two vision scenarios for each use case, one realistic version, aimed at being more achievable and possibly market-ready within a few years after conclusion of the project, and one futuristic version, aimed at being more ambitious but possibly achievable within a larger timespan of 5 – 10 years after conclusion of the project.

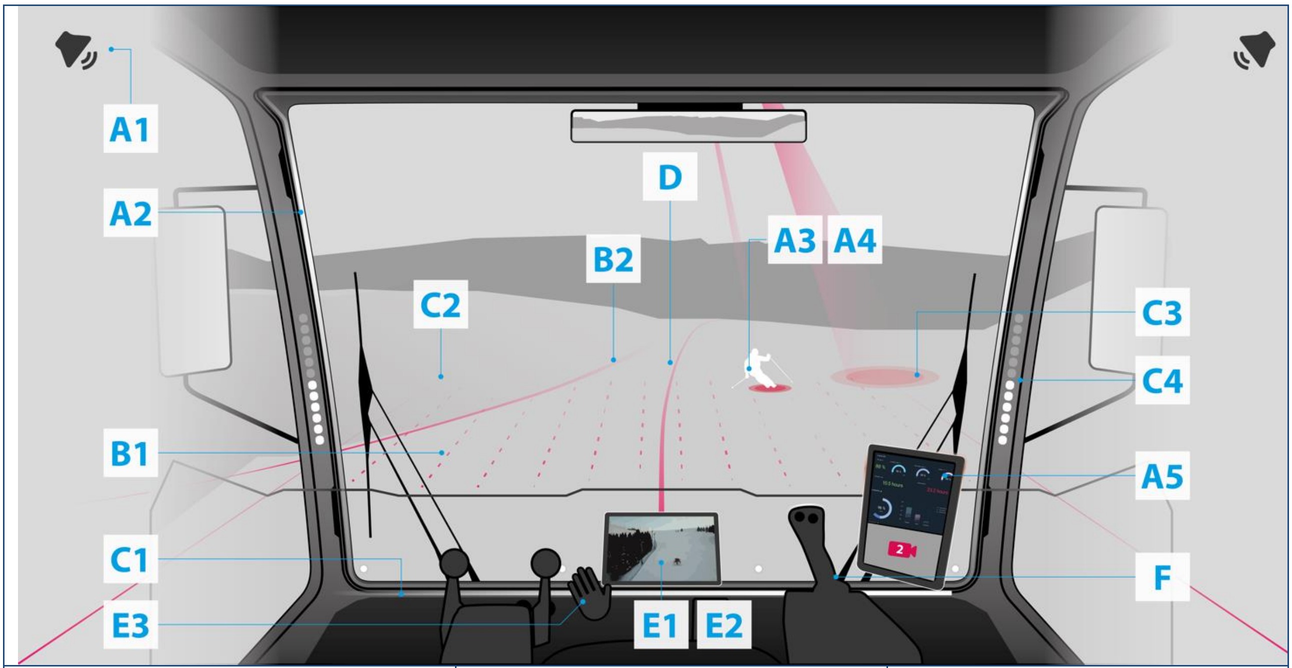
Figure 3: Picture from the UC1 user research in Sterzing, where researchers were able to accompany the operators in their vehicles to gain insights.

The first version of a realistic and futuristic vision scenario for UC1 were completed and shared with the consortium in January 2024. Subsequently, the planning of co-design workshops with operators started in coordination with PRIN, UL, HAP and TUG, which were going to attend the co-design workshops with operators in UC1 along with HdM from the consortium side. The first stage of co-design workshops, focusing on validating and expanding planned technological features (e. g., the smart spotlight or outer lane border projections), was completed in February 2024. The next stage of co-design workshops for UC1, aiming for validating and elaborating information design concepts, is expected to take place in April to May 2024. At the time of writing, it has yet to be determined whether the information design concepts will be elaborated as text-based information scenarios (like originally described by [1]), as graphic wireframes (rough visualisations of information architecture and contents, but not yet final designs) or a combination of both. The validated information scenarios will provide input for more in-depth prototype design.

After the development and validation of information scenarios, the final stage of the scenario-based co-design approach will be the creation of interaction scenarios, which also outline user interactions with the interface and the relevant outputs of the system. For UC1, this stage is expected to take place earliest in May 2024.

2.1.2.2 Information Requirements and multimodal interaction concepts

In supplementation of the co-design approach an expert-based HMI content analysis was conducted throughout WP4/Task 4.1 (see deliverable 4.1). This analysis revealed properties of domain-specific human-machine interfaces for all three use cases. The resulting information range, high-level structure, complexity, and importance of information informed a conceptual phase that defined HMI functionalities for UC1. This conceptual phase also utilized our methodical approach of considering different information presentation modalities suitable for XR interaction (see deliverable 4.2).



A - 360° Object recognition		B – Environment information		C – Tool information	
A1	Surround audio	B1	Snow depth – projection / head -up-display	C1	Blade plunging depth
A2	Ambient light			C2	Blade with
A3	Spotlight	B2	Area Restriction – projection / head-up - display	C3	Track overlap
A4	Classification projection			C4	Shield height offset to target
A5	Video augmentation				
D - Navigation – projection					
E – 3D machine view					
E1	Display visualization	E2	Map view and obstacle visualisation	E3	Gesture view control
F – Realistic Feedback – force feedback in joystick					

Figure 4: Key visual of the XR HMI concept for use case 1 (snow groomer) including annotated functions

As a result, a first version of the multimodal interaction concept of UC1 was created that focuses situation awareness regarding obstacles and target ground profile as critical factors in snow groomer operation (see Figure 4). The XR HMI concept for UC1 comprises of different augmenting information presentations that give the operator additional information about the presence and position of obstacles (A), slope profile (B), tool setup (C,D), navigation and area restrictions (B,D) through different forms of augmenting feedback modalities (visual, acoustic and haptic feedback). This concept informs the following implementation of technologies and continues to explore and define their design visible to the human operator.

2.1.2.3 Development of an iterative methodology for implementation of envisioned XR functions

In the scope of D4.4, we developed a method to translate vision scenarios resulting from the co-design process into functional specifications for UI control and feedback functions, which serve as the basis for engineering implementations of these functions. The approach was devised and put into practice with respect to the design of immersive simulation demonstrators of these functions, however the functional specifications for the simulator functions can just as well serve as a basis for engineering real-world implementations of control and feedback functions for integration into vehicles, as is the focus of work package 6. The approach spans all three THEIA^{XR} use-cases and thus will not be further discussed in Sections 2.2 and 2.3. Please refer to deliverable D4.4 for more details on the devised methodology and current state of the control and feedback function specifications.

2.1.2.4 Identifying Privacy Requirements and Strategies for Mitigating Privacy Risks in Implementations in UC1

To identify the possible risks for privacy in UC1 and to start discussing a mitigation solution, we used the following technologies:

1. Series of questions in the semi-structured interviews [2] with the operators, performed in the frames of co-design workshops, conducted in the frames of T3.1. The questions for the semi-structured interview were developed based on an iterative design approach and followed the purpose of understanding end-users' perception of the data generated by the operation in terms of usefulness for their work and their will to share the data with external entities. The questions were also designed to understand the general privacy concerns of the operators and their perception of the future workflow, including the perception of the factors of automatization of the operations and new data modalities provided by XR. As the iterative process means constant improvement and redesigning of the proposed solutions (in our case, a set of questions and sub-questions [3]) the second round of the semi-structured interview with stakeholders is planned to be made in the start of Month 15. Also, as part of the iterative approach, we transformed the preliminary findings into practical privacy-related questions and integrated them into the realistic and futuristic scenarios described in 2.1.2.1. We plan to test them in the frames of a co-design workshop with operators.
2. Based on the UC1 scenarios, finalized in D2.1, we developed a survey of privacy questions for the stakeholders regarding each of the proposed changes in the basic workflow, using the principles of Data Protection Impact Assessment[1]. The questionnaire helped identify the most privacy-critical parts of the proposed technology development and add privacy concerns to the discussion about the feasibility of proposed solutions.
3. Besides eliciting GDPR-related requirements, we applied the LINDDUN GO methodology [4] to elicitate a broader range of technical and non-technical privacy concerns from stakeholders. To do that, we organized two privacy workshops with representatives of UC1 and technological partners involved in UC1. The results helped identify the most privacy-controversial technologies with the proposals for mitigating the possible privacy risks.

2.1.2.5 Integration of off-the-shelf vibrotactors with force-feedback devices

In order to realize the feedback functions requiring vibrotactile notifications to be provided at the joystick handle (and possibly track control handles for UC1), it was necessary to integrate off-the-shelf vibrotactile actuators with existing Haption force-feedback devices. Ultimately, the aim will be to propose force-feedback device handles with a built-in vibrotactor (see Figure 5 for the current testing prototype) to enable the vibrotactile feedback functions described in deliverable D4.4.

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[1] https://gdpr.eu/data-protection-impact-assessment-template/

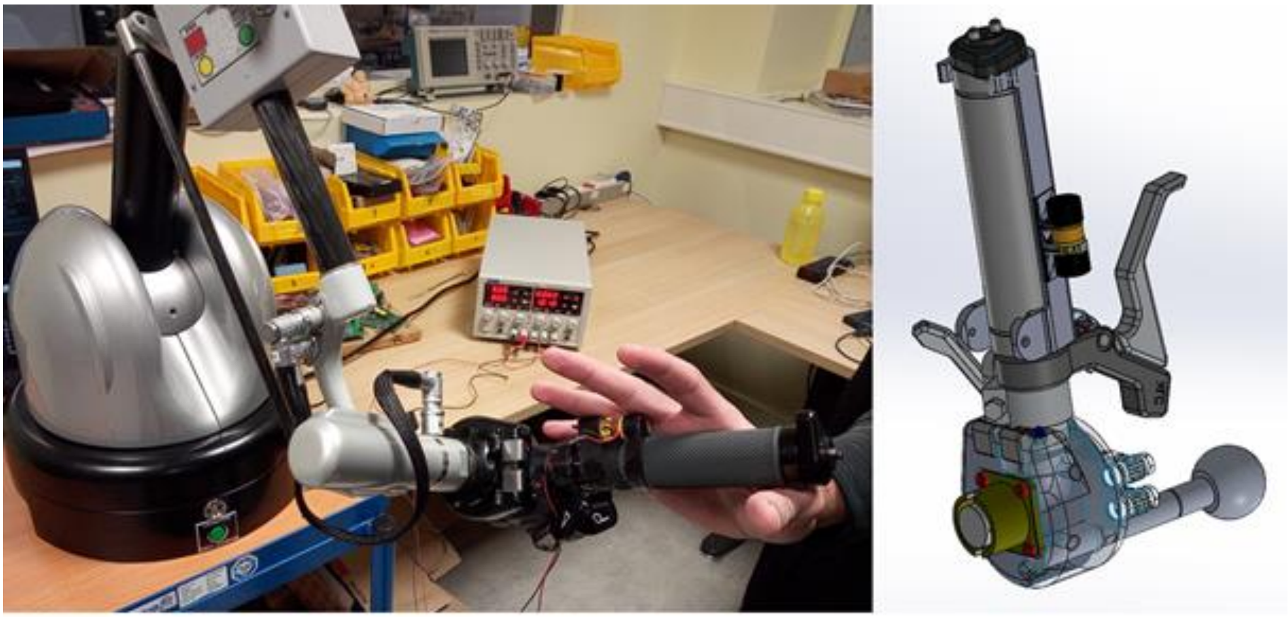

Figure 5: Prototype of Virtuose TREH handle with vibrotactor attached.

The Titan Haptics TacHammer Carlton[2] linear magnetic ram actuator was chosen due to its versatility and sufficient vibration intensity for the applications considered (see initial tests reported in deliverable D5.5).

To drive the actuator, off-the-shelf haptic drivers by Texas Instruments were selected as these provide a simple I²C interface to trigger and generate tactile cues. Ultimately, the aim is to interface an Arduino micro with the controller of the force-feedback device directly via SPI, for the controlling PC (PC running a simulation or in-vehicle IPC) to trigger preset vibrotactile patterns over the same Ethernet or EtherCAT connection as is used to control the force-feedback functions. The Arduino micro in turn will communicate with one or two DRV2605 driver boards[3], each dedicated to a vibrotactile actuator (see Figure 6). Currently, as the controller for the force-feedback device designed by Haption for the THEIA^{XR} project is still under development, a second Arduino micro stands in for it to interface the vibrotactile actuator with the controlling PC via RS232, allowing vibrotactile functions to be prototyped with the final low-level electronics architecture. Since the DRV2605 driver boards do not feature a programmable I²C address, we chose to multiplex the I²C lines (SDA and SCL) between the Arduino micro and the pair of drivers using MAX4544 SPDT Analog Switches[4]. This should ensure the option for bidirectional communication between the Arduino and drivers with a negligible additional power draw and overhead time for switching between targeted actuators. A custom code was developed for the Arduino allowing triggering of preset vibrotactile cues on either one of the two connected vibrotactile actuators.

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[2] https://titanhaptics.com/carlton/

[3] https://www.ti.com/lit/ds/symlink/drv2605.pdf?ts=1710784291997

[4] https://www.analog.com/media/en/technical-documentation/data-sheets/MAX4541-MAX4544.pdf?ADICID=SYND_WW_P682800_PF-spglobal

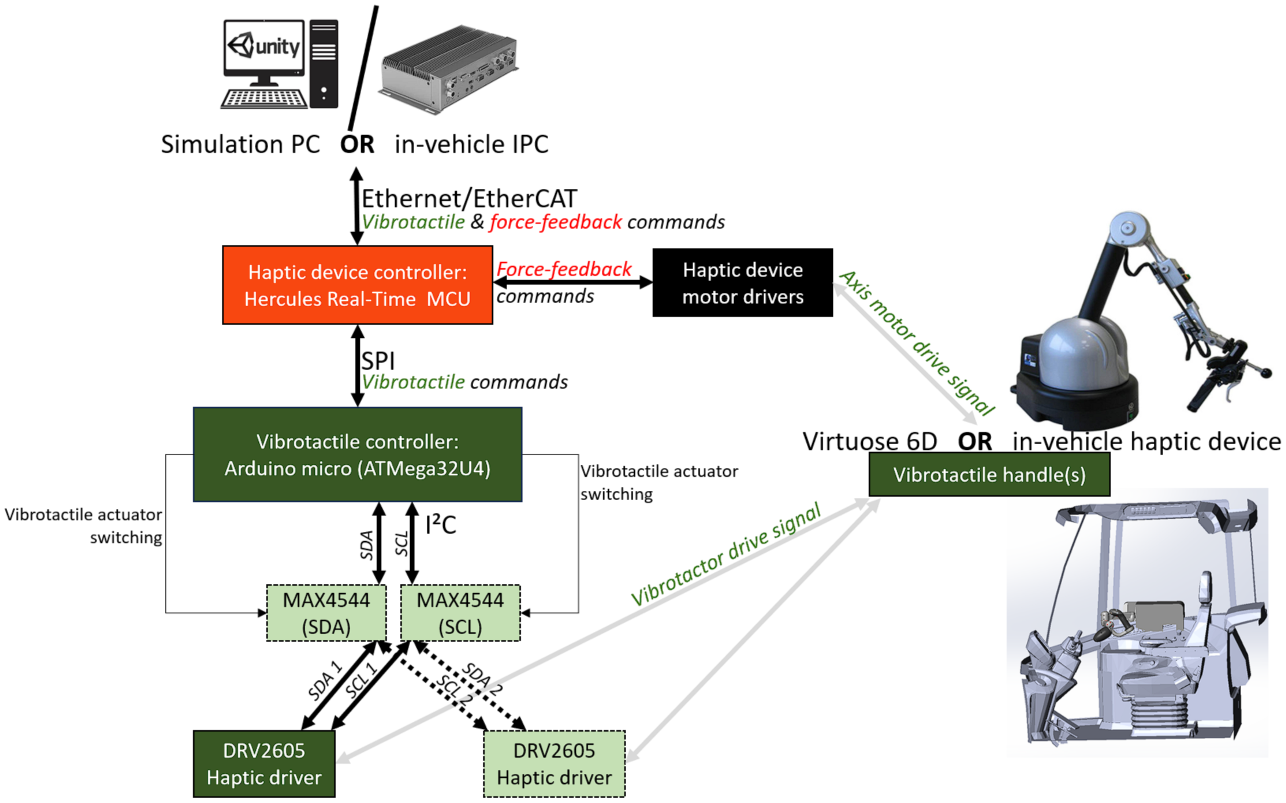

Figure 6: Schematic of the electronics architecture for integrating vibrotactile actuators with the THEIA^{XR} haptic device

The concept for the end-effector incorporating dual vibrotactors is specific to UC1 and targets possible tactile feedback in the vehicle track controls. The integration of a single vibrotactor into the 6DoF force-feedback device handle however is common to UC1 and UC2 and will thus not be discussed further in Section 2.2 below.

2.1.2.6 Snow Groomer Simulator

The snow groomer simulator uses the same Creanex simulator platform as the excavator simulator in UC3. The simulator's components and features are documented more extensively in Section 2.3.2.4, and anything documents there also applies to the snow groomer simulator. The snow groomer simulator functions in the same way and can use all the same features as the excavator simulator, with the difference being only the terrain and machine model. The virtual LIDAR, GPS simulation, projecting markers and visuals to the ground surface, and joint force measurements can and will all be implemented for the snow groomer simulator as well.

LandXML model of the Landurns ski resort in South Tirol in Italy, close to Austria, was imported to the Blender 3D-modeling tool and the surrounding environment was added based on data loaded from opendem.info[5]. The terrain model can be considered as the digital twin of the slope.

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[5] https://www.opendem.info/opendemeu_download_highres.html

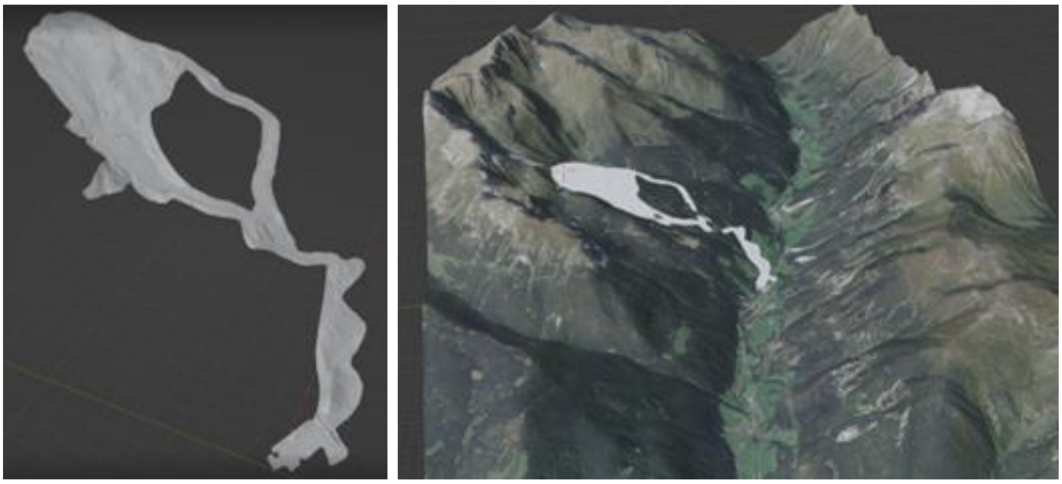


Figure 7: The digital twin terrain model of the Landurns slalom slope.

The 3D model of the snow groomer was provided by Prinoth. The name of the machine type is Leitwolf.

Figure 8: 3D model of the Prinoth Leitwolf snow groomer

The snow groomer has many functions and associated parts that are moved and controlled by the operator. To add the machine model to the Creanex simulation platform, the kinematic structure of the machine parts is defined in a text file. The kinematic structure defines how the parts are joined together, which part connects to which part, and how their joints can move in relation to each other. One of the parts is defined as root, in the case, the undercarriage of the machine, and the other parts form a kinematic structure consisting of the blade, tiller, tracks and winch. Each part, except the root part, has a parent which the part is attached to. The part's offset determines its position and orientation in relation to its parent part. The part can move in relation to its parent part according to its joint configuration. The joints can be revolute (rotating around a given axis), prismatic (moving forwards and backwards along a given axis), or static (fixed, not moving at all). The parts can form tree-like and chain-like structures, with long chains of jointed parts.
The simulator crates a representation of the machine parts, the shapes of the parts and their joints in the physics engine. Section 2.3.2.4.2 explains the physics simulation more thoroughly.

2.1.2.7 Integration of Novel Prototypes on the Snow Groomer

In deliverable 5.1, we developed three novel prototypes, namely a camera-laser setup, a camera-spotlight setup and a panoramic thermal-RGB camera. Both the camera-laser and the camera-spotlight setup can be categorized as work in spatial augmented reality (SAR), while the panoramic thermal-RGB camera is a novel sensor device.

These prototypes correspond to the first iteration, however, we integrated them atop a snow groomer, as depicted in Figure 9. This test yields valuable information regarding future design choices and helps to deepen our understanding regarding the use-cases and real-world requirement in a technological sense, since these prototypes are built with technology not yet tested in such demanding environments.

Figure 9: Integration of the prototypes on a snow groomer.

Depending on the use-case and the prototype in question, the installation and interaction with the vehicle differs. Both SAR prototypes can be operated via image-based control or simulation-based control. The latter requires a thorough understanding on the vehicle's environment and position, since it includes the projection of information from the reconstructed environment into the real world. For this, localization data from the control area network (CAN) bus of the vehicle is required. With a single CAN-USB adapter, data form the vehicles CAN bus can be processed directly on a computing unit. Note that in our experiments, this computing unit was a laptop. After processing this data, we utilize the robot operating system (ROS2) to publish it to our control software, i.e., a simulation environment such as Unity. Subsequently, this information is processed and sent to the prototype in an appropriate format. For instance, the format for the control information of camera-spotlight prototype, is the direction in which the light cone should be pointed. An exemplary visualization of this information flow is depicted in Figure 10.

The image-based control does not require position information of the vehicle's CAN bus nor a reconstruction of the environment. Similar to the thermal-RGB prototype, the information flow is different, yet simpler. Here, the sensor data is forwarded to the computation unit where image processing is applied.

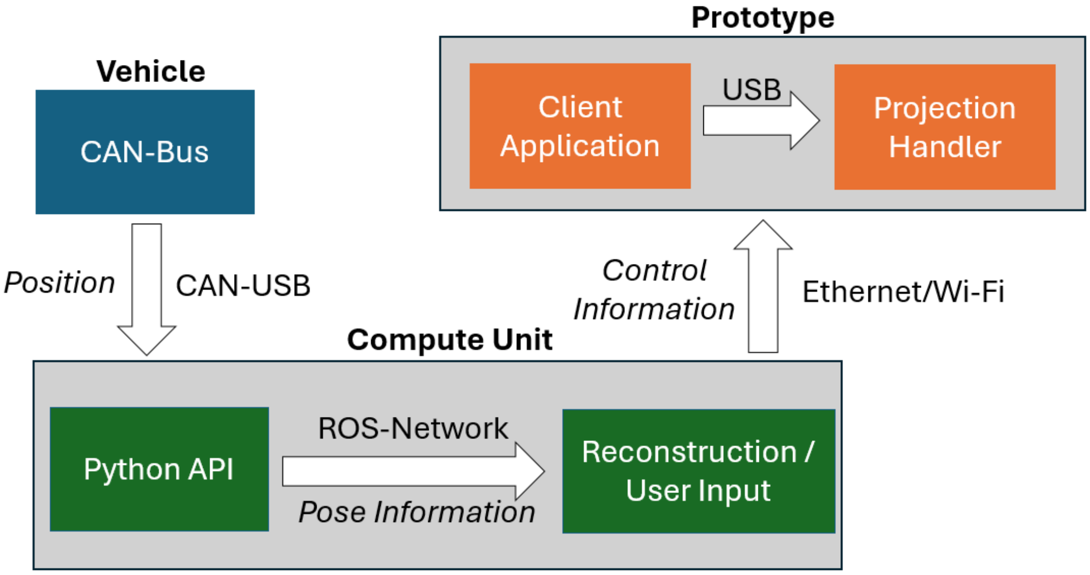


Figure 10: Schematic visualization regarding the information flow between vehicle and prototype.

2.1.2.8 *Data Handling and Processing Infrastructure*

To finally integrate all the technologies into the demonstrator, a central computing and processing infrastructure is required that is capable of collecting all the data coming from the relevant sensors and transferring the data again to the output devices, like the acoustic, haptic or visual outputs. Additionally, the applications that will interpret the collected data and transform it into understandable feedback for the human operator need to be hosted also on the infrastructure. This all needs to be done within the mobile machinery, without being dependent on external computing sources, like cloud infrastructures.

Within Task 5.3 – Visualization Infrastructure and Interaction System, the central computing infrastructure is being developed, including the interfaces for connecting to the other technologies, like visual, acoustic, and haptic feedback devices. At the current phase of this deliverable, the infrastructure is not yet available for integration into the machine but is still under development in the respective task.

The data coming from the different data sources (e.g., sensors) is mainly coming over the general communication buses available within the snow groomer, which are mainly CAN and Ethernet channels.

The aim is to have an infrastructure that is ruggedized and able to handle environmental situations from the off-highway domain.

The integration plan is that the infrastructure will first be integrated in a Hardware-in-the-Loop environment including simulated environments, as depicted in Figure 11. Data will be coming from the simulated environments, including potential simulated sensor data, and can be used to test the infrastructure integrated with other technologies (e.g., haptic, visual, acoustic, etc) without directly going to the mobile machinery. This can be seen as the lab integration, which will be first step towards the final integration into the actual machinery.

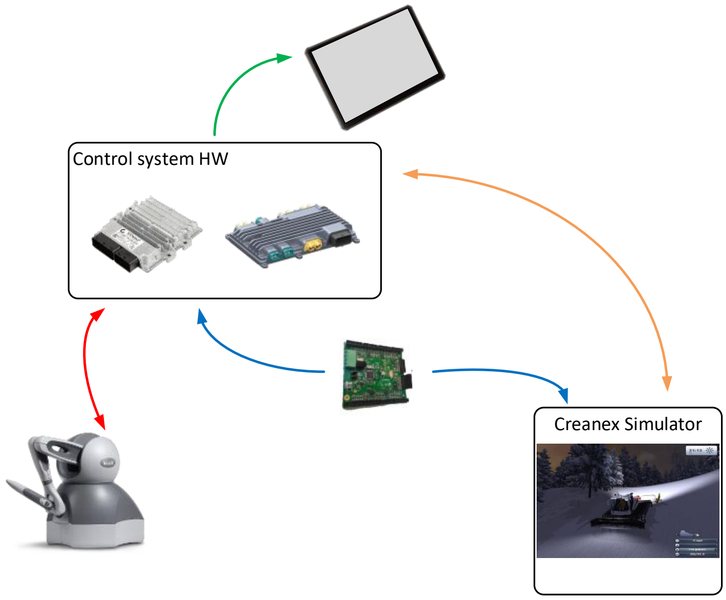


Figure 11: HiL integration of data handling infrastructure

The final integration into the machinery is planned for the second phase of the project, where the majority of the technologies will be available and also tested (mainly in lab environments, but some maybe in real environments). The final integration of the infrastructure is planned with the real machine, as schematically depicted in Figure 12. The next step for the integration is to focus on the individual technologies being developed by the separate partners and integrate it with the actual hardware, thereby defining all the necessary interfaces required to interact with the sensors, actuators and output devices. For the final integration in the machine, close interaction with partner PRIN is required for understanding the architecture of the snow groomer and having access to all the communication networks in the machine.

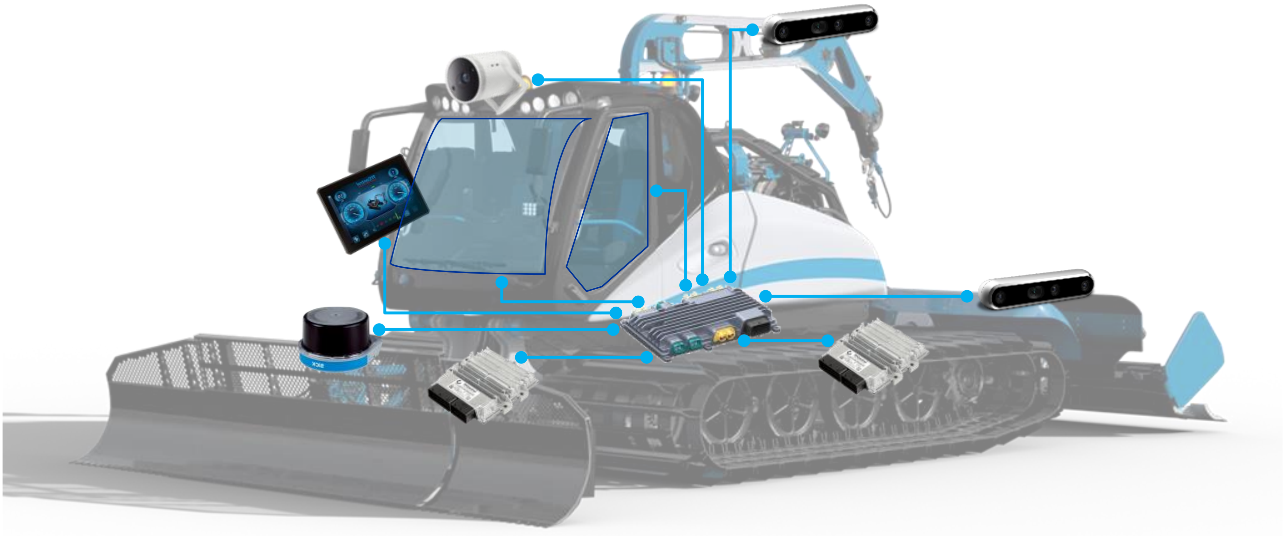


Figure 12: Schematic overview of integrated infrastructure into UC1 demonstrator

The deployment of the software on the infrastructure is planned to be as smooth as possible. The aim is to use a dockerized approach, where all the required software (i.e., applications, drivers, etc.) is provided to the system integrator and can be easily deployed and tested on the real hardware.

2.1.3 Next Steps

Developed THEIA^{XR} technologies and methodologies as described above will be implemented in a real snow groomer or into the demonstrator cabin or into both. For a smooth and successful implementation, the requirements and interfaces will be defined beforehand. To install hardware devices the snow groomer is prepared to allow an easy installation. A CAN bus connection is in place to read out requested live sensor data from the snow groomer during operation.

2.2 Use Case 2 – Logistics

A smart container yard includes systems for intelligently controlling the operations of vehicles like reach stacker in the container yard using teleoperation and/or autonomous operations. A remote support server controls remote support sessions associated with vehicles in the container yard to provide teleoperation support for loading and unloading operations. In the future, aerial drones may be utilized to maintain positions above a teleoperated vehicle and act as signal re-transmitters. Augmented reality views may be provided at a teleoperator workstation to enable a teleoperator to control vehicle operations in the smart container yard.

For use case 2, several scenarios were considered and demonstrated: realistic, short-term scenarios as well as visionary, long term scenarios for both traditional and remote driving of reach stackers.

2.2.1 UC2 Infrastructure

This section describes the infrastructure of the demonstrator: a technical overview of the reach stacker and how the developed THEIA^{XR} technologies can be or are already integrated.

The first step for integrating a new control system to the real machine is to test it with the Hardware in the Loop (HIL) simulator. The simulator can be used for developing and validating reach stacker functionality and behaviour in remote control operation. This includes driving and load handling with the machine in remote control mode. The simulator and Unity visualization can also be used for camera location validation. The selected demo machine is the Kalmar Eco reach stacker DRG450 65S5. The reach stacker's operational dimensions are shown below in Figure 13.

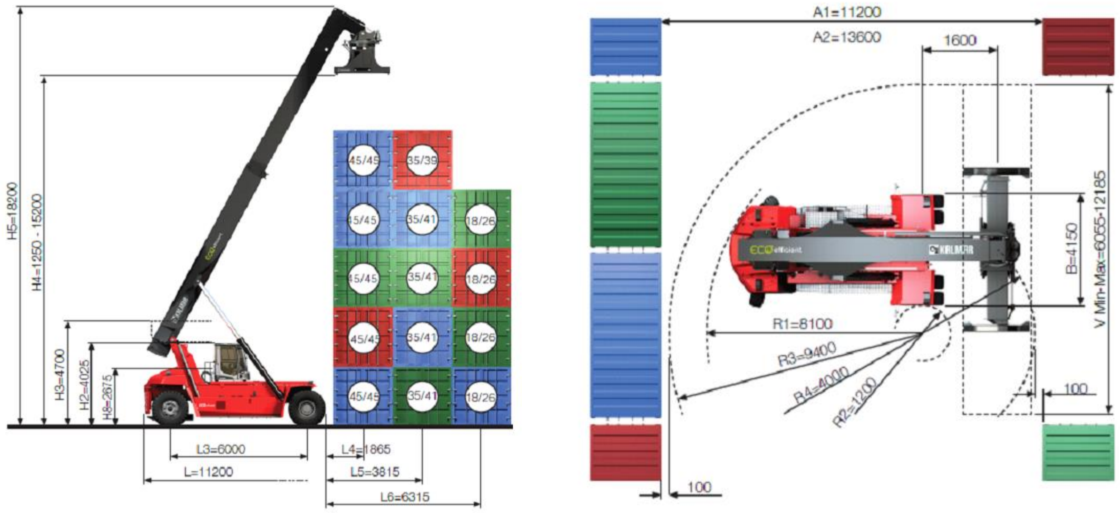


Figure 13: Kalmar DRG 450 65S5 operational dimensions

Figure 14: Test site in Ljungby, Sweden, where user tests took place in December, 2023

The final demonstrator for use case 2 consists of:

- a RC desk setup and
- a Kalmar Eco reach stacker at Ljungby, Sweden as a realistic demonstrator platform.

The RC desk features e.g., the following technologies:

- Ergonomic remote control desk
- A big PC screen
- AR overlays on video screen, such as
    - Assisting AR features for remote operator showing for example the correct path for the spreader to the corner castings
    - A simulated 3D LiDAR view of corner castings
    - A virtual rear-mirror that displays the obstacles in the back
- A touch-screen control panel to control and monitor the machine
- Joystick for boom control
- Steering wheel and pedals for driving
- E-stop button

The reach stacker has been equipped with the following sensors:

- A LiDAR scanner positioned on the lower face of the boom
- An RTK-GNSS system to measure position and heading of the boom tip
- Video-cameras
- 360° camera
- Microphones for 3D spatial audio
- A front-facing stereo camera on the tip of the boom

With the help of these sensors, the following AR-technologies will be demonstrated:

- Indication of current spreader status and position:
    - A LED-light-panel on the bottom-side of the boom showing the status of twistlocks and land-pins

    - Augmentation of the video-stream of the front facing camera
- Warning signals in case of a detected person in the danger area of the reach stacker
    - Visualization of the position and distance for the detected persons with AR overlay on the screen (human surrounded with bounding box)
- 3D spatial audio for warnings
- 3D LiDAR view visualization to help the user position the reach stacker's spreader twistlocks to the corner castings
- Gesture-based UI control: Hand-tracking feedback feature for changing the main camera view
- Haptic feedback

2.2.2 Integrated Technologies/Methodologies

2.2.2.1 Application of Co-Design Methodology in UC2

Due to the transdisciplinary co-design approach running in roughly the same way and timespan in all use-cases, this section will me mostly identical to Section 2.1.2.1, only deviating in dates and details of the process.

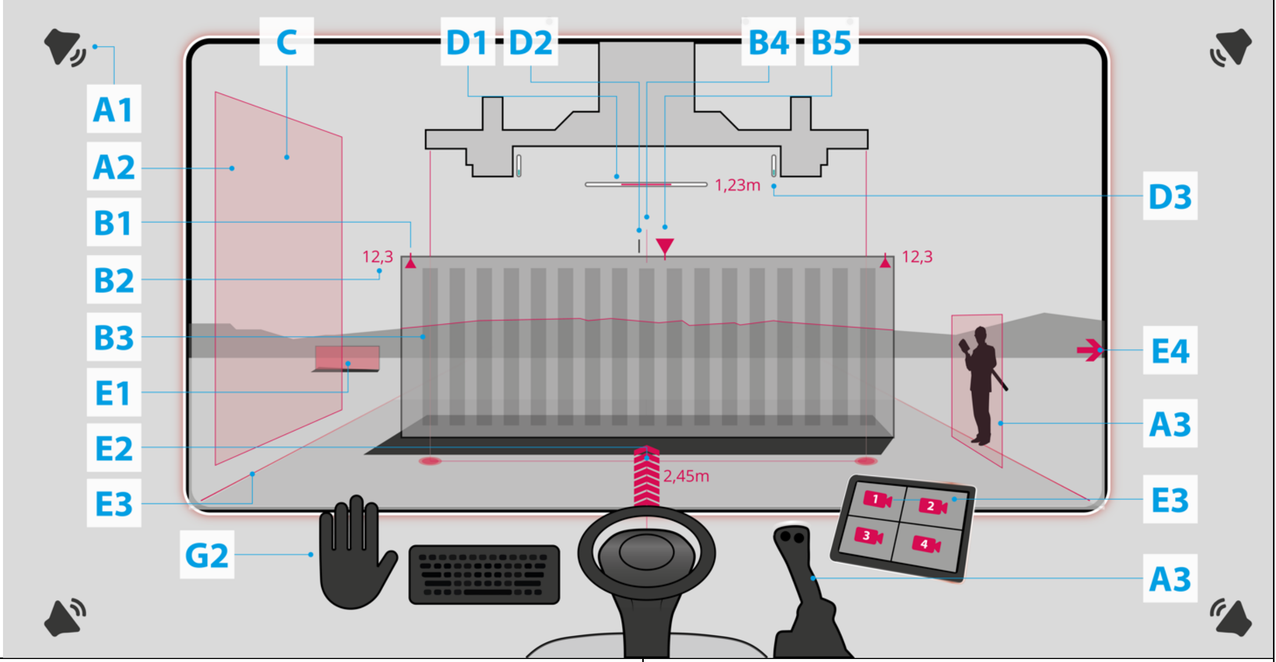
Following the user research conducted in Hanko, Finland, and Ljungby, Sweden, as part of T3.1, a problem scenario was defined (first step of the scenario-based design approach), describing a current typical reach stacker operation. This scenario was shared with the consortium. On December 15, 2023, an ideation workshop was held involving all active partners in this use-case. In this workshop, ideas for technology usage and some concepts already in development were collected and discussed in terms of their technical feasibility and expected utility for the operators. It was assumed that operators may have difficulties coming up with technology usage and interaction ideas on their own and may both over- and underestimate what is currently technically possible. Thus, the input from project partners was going to be implemented into a first activity scenario version, providing examples of how XR technology could realistically support operators at work and serving as a basis for the idea generation and validation with operators.

For explanations of the naming and background of realistic and futuristic vision scenario, see Section 2.1.2.1.

The first version of the realistic and futuristic vision scenarios for UC2 were completed and shared with the consortium in January 2024. Subsequently, the planning of co-design workshops with operators started in coordination with KAL and VTT. At the time or writing, contact acquisition efforts to involve actual end-users from harbour terminals in the co-design process are still ongoing.

2.2.2.2 Information Requirements and multimodal interaction concepts

Similarly to UC1, a HMI content analysis was conducted throughout WP4/Task 4.1 (see deliverable 4.1) for UC2. This analysis revealed the importance of spatial information regarding the environment and spreader of the reach stacker. The resulting information range, high-level structure, complexity and importance of information informed a conceptual phase that defined HMI functionalities for UC2. This conceptual phase utilized our methodical approach of considering different information presentation modalities suitable for XR interaction (see deliverable 4.2), likewise resulting in a first version of the multimodal interaction concept for UC2 (see Figure 15).



A - 360° Object recognition		B - Load Information – visual video overlay	
A1	Surround audio	B1	Corner pins position
A1	Ambient light	B2	Corner weight
A3	Visual Overlay	B3	See Through Container
C - Visual Load Chart – visual video overlay		B4	Centre line of container
D – Tool information – visual video overlay		B5	Centre of mass
D1	Centre line of Vehicle	E – Navigation – visual video overlay	
D2	Distance to Container	E1	Container target position
D3	Spreader status	E2	Path of vehicle movement
F – View Control		E3	Area limitation
F1	Tablet interface	E4	Route indicator
F2	Gesture tracking	G – Realistic Feedback – force feedback in joystick	

Figure 15: Key visual of the XR HMI concept for use case 2 (reach stacker) including annotated functions

Supporting the operator to perceive spatial information from the real environment and to stay aware of items not visible in the cameras is a challenge. Since the visibility and feeling of presence (the sounds, vibration and movement of the machine) are not going to be on the same level in remote operation than driving a machine from the cabin, it is very important that the operators feel that they are controlling the machine in a safe and predictable manner, and they have enough information about the surroundings. The XR HMI concept for this use case comprises of different augmenting information presentations that give the operator additional information about the presence and position of obstacles (A), tool and cargo properties (B), and navigation and area restrictions (B,D) through different forms of augmenting feedback modalities (visual, acoustic and haptic feedback). This concept informs the following implementation of technologies and continues to explore and define their design visible to the human operator.

2.2.2.3 Identifying Privacy Requirements and Strategies for Mitigating Privacy Risks in Implementations in UC2

To identify the possible risks for privacy in UC2 and to start discussing a mitigation solution, we used the following technologies:

1. Series of questions in the semi-structured interviews [2] with the operators, performed in the frames of co-design workshops, conducted in the frames of T3.1. The questions for the semi-structured interview were developed based on an iterative design approach and followed the purpose of understanding end-users' perception of the data generated by the operation in terms of usefulness for their work and their will to share the data with external entities. The questions were also designed to understand the general privacy concerns of the operators and their perception of the future

workflow, including the perception of the factors of automatization of the operations and new data modalities provided by XR. As the iterative process means constant improvement and redesigning of the proposed solutions (in our case, a set of questions and sub-questions) [3], the second round of the semi-structured interview with stakeholders is planned to be made in the middle of Month 15. Also, as part of the iterative approach, we transformed the preliminary findings into practical privacy-related questions and integrated them into the realistic and futuristic scenarios described in 2.1.2.1. We plan to test them in the frames of a co-design workshop with operators in line with the timeframes proposed in 2.2.2.1.

2. Based on the UC2 scenarios finalized in D2.1, we developed a survey of privacy questions for the stakeholders regarding each of the proposed changes in the basic workflow, using the principles of Data Protection Impact Assessment[6]. The questionnaire helped identify the most privacy-critical parts of the proposed technology development and add privacy concerns to the discussion about the feasibility of proposed solutions.
3. Besides eliciting GDPR-related requirements, we applied the LINDDUN GO methodology [4] to elicitate a broader range of technical and non-technical privacy concerns from stakeholders. To do that, we organized two privacy workshops with representatives of UC2 and technological partners involved in UC2. The results helped identify the most privacy-controversial technologies with the proposals for mitigating the possible privacy risks.

2.2.2.4 *Augmented reality via 360° video feed*

Augmented reality via 360° camera video feed can be achieved by utilizing computer vision methods. For example, the front or top surfaces of the container can be tracked with a calibrated camera by using markers of feature matching. The ultrawide field of view of the 360° camera will be a problem for camera calibration, but since those cameras have linear FOV rising from the centre of the sensor for images to be projected on spherical proxies for viewing, it is possible to reduce FOV by cropping the image. Using this method, it is possible to calibrate a stereo 180° camera with an OpenCV fisheye camera model and stereo calibration module. By tracking objects with the calibrated camera, it is possible to get the object's transform relative to the camera position in real scale and use that information to overlay AR guidance features on top of the real-world objects in 360 camera video feed with correct perspective transform.

Tracking people, obstacles, and generic moving objects in the camera feed can be done in screenspace with frame differencing and background subtraction, without applying the perspective transform. A simple bounding box can be fitted to the object to highlight it.

Another possible way to achieve AR via 360 video feed is to integrate an already existing solution such as Real-time eXtended Reality Multimedia[7] from Nokia. According to the feature list, it already includes multi-view streaming from 360 cameras, visual overlays for IoT sensor data, video analytics solutions, and 3D spatial audio.

2.2.2.5 *Haptic control*

Haption's Virtuose 6D device was used to simulate a force-feedback-enabled joystick. The joystick mapping follows the real reach stacker control system, with the x-axis controlling the boom extension, and the y-axis controlling the boom angle.

During the third user test that was held in VTT's premises on Feb 27th, 2024, users were able to try a force feedback feature where the joystick forward rotation (that rotates the boom downwards) would block when the container touched the ground (or the target truck's flatbed). Users provided overall positive feedback about the feature, even though the testing time for that was very short and there wasn't a specified goal to the task, but rather to move the spreader around and feel the force feedback. Future developments could involve making the user feel the weight and torque applied to the reach stacker by the container, as well as proximity of the container to other containers when the container needs to be placed in a tight space between other containers.

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[6] https://gdpr.eu/data-protection-impact-assessment-template/

[7] RXRM, https://www.nokia.com/industries/rxrm/

Figure 16: Integrating a Virtuose6D haptic interface with the UC2 simulator

Haption iteratively refined the first version of the “*HapticServer*” software interface developed for interfacing a 6DoF haptic device (currently a Virtuose6D device, to be replaced by the custom haptic interface developed for the THEIA^{XR} project in the future – see deliverable D5.5) with the simulations, and possibly vehicles, developed in the scope of THEIA^{XR} in collaboration with VTT. This software interface provides inputs in the form of position and orientation values (raw or normalized with respect to the haptic device range of motion) and takes high-level force and torque definitions stemming from the task-specific haptic feedback mappings designed in deliverables D3.4 and D4.4, converting them to adequate setpoints for the haptic interface. By specifying axis locks and limits to the ranges of motion it was possible to simulate the mechanical behavior of a variety of input device kinematic structures and mechanical properties (damping and stiffness when applicable).

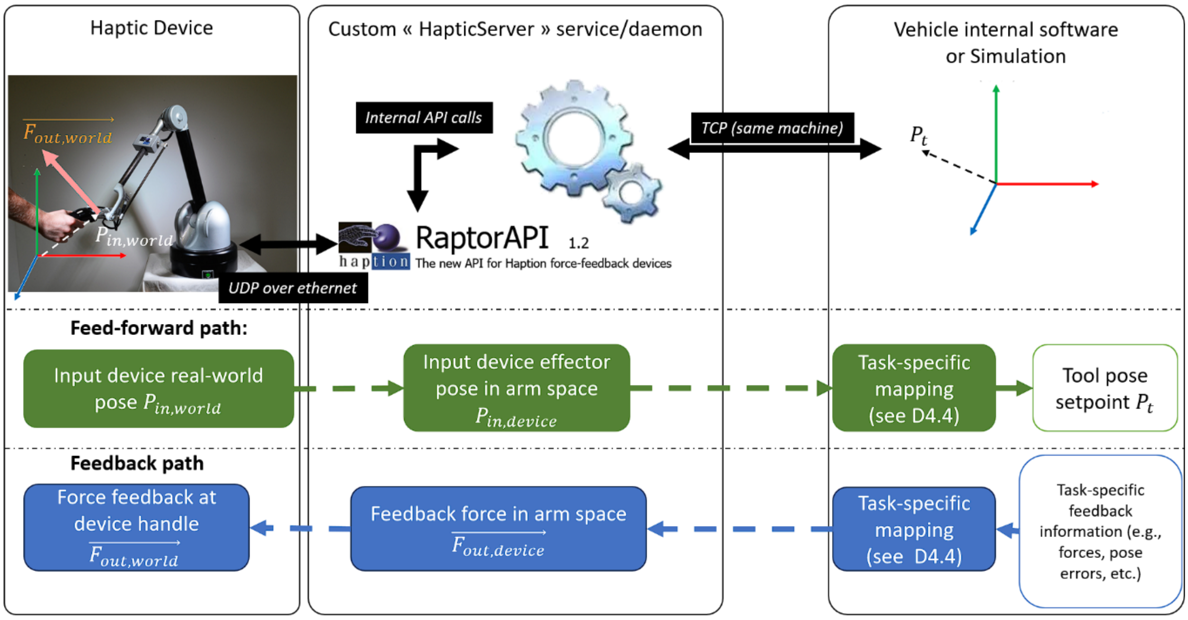

Figure 17: Architecture of the interface between haptic I/O device and simulation or vehicle functions

Initially, a dedicated “*HapticServer*” software running as a Windows service was prototyped in the context of deliverable D3.4 and D5.5 (see Figure 17). By interfacing the Virtuose6D device with a simulated reach stacker teleoperation environment over the course of January and February 2023 (Figure 16), the requirements towards the HapticServer software and its interfaces were iteratively refined (Figure 17). In principle, designing the HapticServer software to fulfil the functions depicted in Figure 18 should allow the implementation of all control and feedback functions relevant to THEIA^{XR} both in simulation (see deliverable D4.4) and in-vehicle, for the functions that may be realized as such, as is the focus of work package WP6.

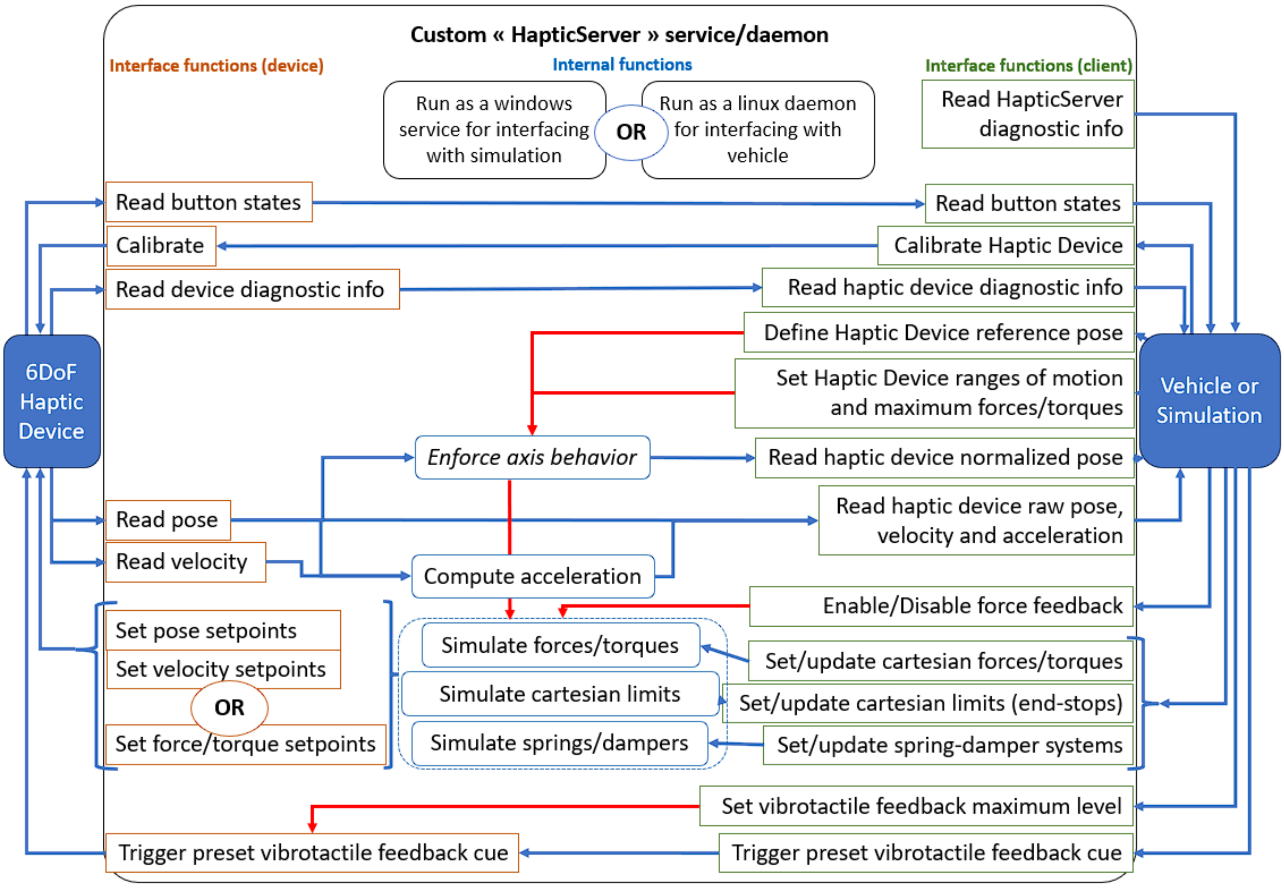

Figure 18: HapticServer software functional architecture (blue lines represent information flow through the HapticServer, while red lines represent the flow of internal configuration information)

As shown in Figure 18, the currently specified architecture for the "HapticServer" defines a set of interface functions on the haptic device side, enabling retrieval of pose, diagnostics, and handle button input information as well as triggering of calibration. Furthermore, on the device side, the software provides the possibility for setting device setpoints as well as triggering preset vibrotactile effects in the handle. On the client (simulation or vehicle internal software) side, the software provides a set of functions for:

- Setting haptic device mechanical behavior (zero pose, ranges of motion, maximum forces and torques).
- Retrieval of pose (raw or normalized), diagnostics, and handle button input information as well as triggering calibration.
- Enabling/disabling of haptic feedback, as well as setting or updating of at least three types of feedback cues:
    - Constant cartesian forces or torques (to be applied at the handle)
    - Cartesian limits (virtual end-stops)
    - Virtual spring-damper systems
- Configuring vibrotactile feedback intensity and triggering preset vibrotactile feedback cues.
  While the current architecture may be suited to porting to a Linux IPC platform for in-vehicle integration, this step will largely depend on decisions made with respect to the control of safety-

critical vehicle functions. Indeed, the current software platform is designed with the control of simulated functions in mind and may require significant redesign if more safety-critical functions are targeted in WP6.

2.2.2.6 3D sound for warnings

3D spatial audio can be captured in the following ways:

- Mono recording
- ORTF stereo recording
- Binaural recording
- Ambisonic multichannel recording

Mono recording can be done with a single directional microphone and is useful when recording a single audio source. The position of the audio source can be perceived in relation to the recording microphone while using headphones or integrated audio of a VR headset.

ORTF stereo recording uses two cardioid microphones at the angle of 110° roughly 17 cm apart. This technique could be useful to record sound from inside the vehicle cabin to imitate binaural hearing.

Binaural recording is done with a pair of omnidirectional microphones placed in a dummy model of the operator’s head. This technique is more precise than ORTF recording, especially if head tracking is utilized and the dummy head model pose is synchronized with the operator’s head pose.

Ambisonic recording is done with a multi-channel microphone to produce a 360-degree audio field. Due to the wide range, ambisonic recordings are more suitable for ambiance and soundscapes.

2.2.2.7 Gesture-based UI control

Hand tracking was used to handle UI elements and camera views on the screen. Only left hand was tracked for this prototype, given the assumption that the right hand would be used to control the reach stacker joystick and other devices.

A swipe gesture feature let users change the main camera view visible on the screen (the application includes four different 360° camera streams). Users can either swipe “forwards” or “backwards” to visualize the next or the previous camera stream. The gesture is set to recognize when the hand’s palm normal is parallel to the ground (with an error margin of about 15°), and it fires an action whenever the hand’s palm reaches a specified speed (and then slows down) with its normal always being parallel to the ground.

A pinch-to-rotate gesture was implemented to allow the user to navigate inside the 360-degree camera stream. When the user pinches with their thumb and index finger the gesture activates, and moving the hand up, down, left or right makes the camera view rotate in the specified direction. The gesture deactivates when the user stops pinching (i.e., when they spread the thumb and index).

When the operator uses any of the hand-tracking features, they are made aware of the input the application is receiving, and how it is responding to that thanks to an “hand tracking feedback” widget (see Figure 19). A small sphere represents the hand position relative to the hand-tracking device. If the sphere is orange, it means that no hand is being tracked. If the sphere is yellow, it means that the hand is tracked but it is outside of the allowed interaction area (visualized as a transparent dome). Finally, when the sphere is green it means that the hand is being tracked and the operator can perform gestures.

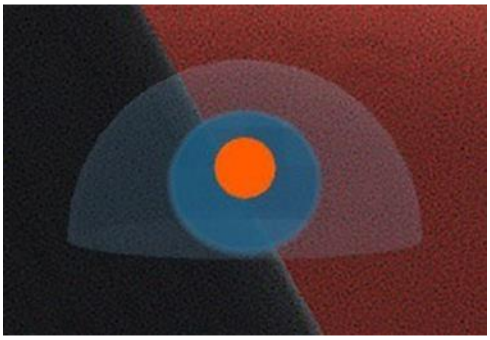

Figure 19: Screenshot of the hand tracking feedback feature. The sphere is currently orange because no hands are being tracked.

2.2.2.8 LiDAR visualization

On the application display, the user is also shown a simulated "LiDAR view", that brings together a virtual representation of the reach stacker's spreader (obtained through the vehicle's IMU), and a point cloud of the container (obtained through a LiDAR scanner positioned on the lower face of the boom). This feature can be useful to double check with camera sensor and in situations where some cameras are less useful (for example, when the container must be placed on a tall stack and it's harder to see it in the front camera). Also, by creating a of digital twin of the real world it allows the user to explore the scene in 3D and removes issues caused by 2D imagery.

The simulation can have an arbitrary number of lidar points, but a large number of them could significantly affect the application's framerate (in a real work environment the bottle neck would be on the physical sensor, rather than on the graphics performance). The best trade-off between quality and performance that was used during the final user test was thus having 10.000 rays casted towards a specific corner of the container (the user could also choose to look at another corner) with an angle of 30° both on azimuth and zenith angles. In the simulation, a virtual Lidar sensor was put on the lower face of the boom, facing towards the currently selected corner of the container. That position seemed to be the best trade-off between providing as much lidar information as possible, and keeping the simulation feasible for an implementation in the real world.

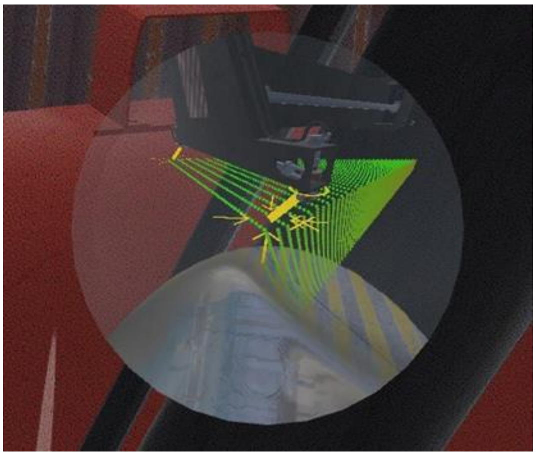

Figure 20: Screenshot of the Lidar view feature. The reach stacker's spreader is visible thanks to the vehicle's IMU data, while the container becomes visible thanks to the lidar points captured by the lidar sensor.

2.2.3 Next Steps

For the next steps in the integration process, the control environment provided by VTT will be integrated to Kalmar's HIL simulator. This includes data integration and testing performed with the simulator at the Kalmar lab.

For testing wireless communication with 5G, the next steps include working with the Nokia Real-time extended Reality Multimedia (RXRM) team and setup of 360° video and audio. In this project we decided to experiment with having the remote-control desk and the machine itself are in different countries. This is the first step towards central control of many terminals. The next step is to establish a remote connection between RC desk at Tampere, Finland and the reach stacker which is physically located in Ljungby, Sweden. Next steps may also include thermal camera setup, and the same communication setup can be utilized for that.

For the setup of 'See-through' for the reach stacker, a stereo camera will be installed to the boom tip. The intelligent camera features allow detecting humans that are behind the container. The persons can be highlighted with a bounding box as an overlay on the screen. Also, other features can be highlighted when needed.

For these next steps, it is necessary to prepare the reach stacker machine and the environment for the tests. This includes finalizing the integration of the control system with the machine as well as the e-stop arrangements at the test yard.

2.3 Use Case 3 – Construction

2.3.1 UC3 Infrastructure

Use Case 3 consists of 2 demonstrators: a standalone cabin for rapid HMI-prototyping and a CASE WX185 excavator as a realistic demonstrator platform, as depicted in the following picture.

Figure 21: The 2 demonstrators for use case 3: a prototyping cabin and an excavator

The standalone cabin is a mock-up seat box, with a modular and scalable cabin-like frame, a real excavator seat and two custom armrests. It can represent various sizes and shapes of cabins and provide attachments and configurable spaces to implement various interaction technologies (e.g., touch-displays, physical control-elements, tracking sensors).
Within THEIA^{XR}, we significantly advanced the capabilities of the cabin as it got equipped with projectors, industry-grade excavator joysticks, an ambient light system, an audio system and a data interface to communicate with simulation environments.

Modular armrest: Control armrests are a key part of HMIs of off-highway machines. They usually house physical controls linked to main machine functions (e.g., operation modes, power switches, hydraulic controls, and joysticks for machine and tool control). Conventional control armrests are rather sophisticated regarding ergonomic design and optimized for “blind” operation (being able to identify and use physical controls without looking at them). However, new control technologies, such as touch pads, touch-displays, gesture tracking sensors, and advanced light feedback are available today but are rarely considered as their use requires a consolidated HMI approach that connects digital data, virtual visualizations and physical control elements. Significantly improved interaction performance or safety must justify the associated higher hardware costs. To ease exploration and conceptualization of HMIs regarding these new technologies, the modular armrest of the cabin provides a modular hardware-software framework, that allows to combine and plug-and-play installation of various interaction components on the armrest (see figure). The software TouchDesigner[8] is used to organize data input and output and to connect the controls and output media to each other and a simulation environment.

Inside projection: Besides consumer-grade touch displays that can be installed on several places within the cabin, short-throw mini beamers are used to project complex visualizations inside the cabin. One projector covers the front screen and enables the projection of side or back mirror displays, or terminal displays. Another projector covers the right armrest from above able to project visual cues onto the physical controls. Data stream for the projectors is implemented into the central data handling software, enabling a synchronized behaviour with simulated environments, machines behaviour, and other HMI components.

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[8] https://derivative.ca/

Outside projection: For exploration purposes, another beamer is used to realize projections in the vicinity of the cabin. Even though using a home projector which only provides limited brightness, testing of ground projections in front of the cabin can be demonstrated and explored.

Ambient light, audio and haptic feedback: Key modalities of extended reality in THEIA^{XR} are light, audio and haptic feedback that is used to convey assistive information on machine state and processes. To experiment with different signal combinations, designs and behaviour, the software media controller is able to feed led-strips, speakers and vibration motors. A set of lightbars around the windscreen and the terminal display are already integrated.

A CASE WX185 mobile hydraulic excavator will be used as a demonstrator. The excavator itself is a conventional excavator with electric-hydraulic control, 4-wheel drive and a monoblock-boom and a very simple user-interface. To implement sophisticated XR-technologies and novel user-interface-modalities, the excavator will be enhanced with additional sensors to provide information for the user that are beyond the current status-quo.

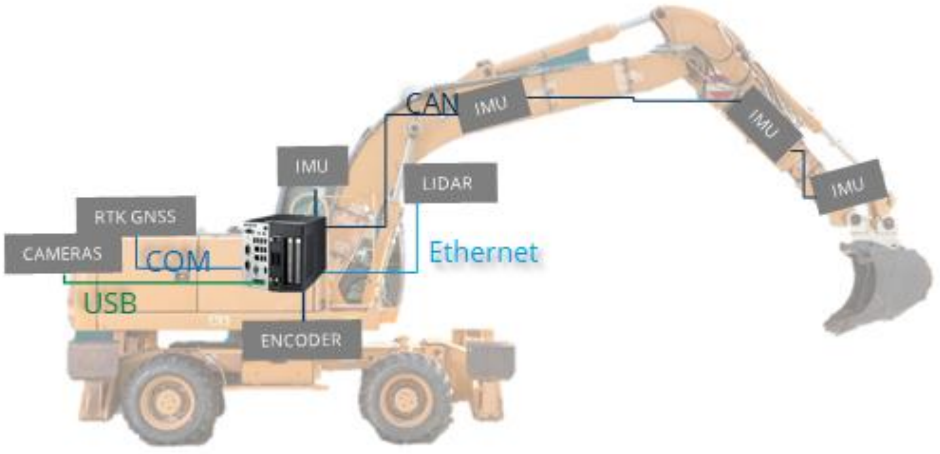


Figure 22: Sensor equipment for the excavator

The following sensors will be added to the excavator:

- Kinematic sensors (inertia measurement for dynamic inclination measurements) at the cabin, boom, arm and tool to sense the motion of the working equipment.
- A rotary encoder to measure the slewing angle between upper carriage and lower carriage.
- An RTK-GNSS system to measure the geo-referenced position and heading of the upper carriage including 2 antennas. The rtcm-corection data is provided by an industrial PC with internet connection.
- USB-Video-cameras on the upper carriage to view the left, right and rear of the machine. The RGB-data can be used to apply AI-based person and object detection to inform the operator about potential risks of collision.
- A front-facing 3D-Lidar at the cabin roof to measure the actual topology of the working area.
- A front facing video camera on the cabin roof for video augmentation of the working area.

Additionally, to the real-time sensor data, geometric data of the excavator, calibration measurements of the sensors and digital terrain models as well as digital models of the subsurface pipes and cables are used to construct a high-fidelity virtual representation of the machine and its surrounding.

Besides the sensors, additional computing and visual feedback devices will be added:

- A 14"-touch display as main-input and visualization device mounted in front of the right A-pillar in portrait mode.
- An industrial PC that works as a central data hub and computing platform. All sensor interfaces, CAN-Buses and visual interfaces are connected to the IPC.
- A computing platform to compute the person and object detection based on the RGB-videos of the surrounding.
- An LED-matrix display at the bottom of the excavator’s arm.
- Several light indicators to inform about potential collisions.

With the help of the described technologies, the following XR-features will be demonstrated:
The excavator operator needs to dig in a specified height with a tight corridor of tolerance (<3cm). The indication of the current tool position with respect to a digital design model will support the correct earthwork. The following modalities are meant to provide a comprehensive view on the current precision of the tool-movement:
For UC3-scenario 1, the following technologies will be implemented:

- A side-bar-widget in the touch-display to illustrate the deviation of the left and right edge of the bucket. The color-coded bar indicates in discrete steps the deviation in height.
- A LED-matrix-panel on the bottom-side of the arm, that can show images in a 16x16-matrix. The same colour-and arrow-coding as in the display is used to visualize the deviation in height.
- An AR- front-window-projection next to the A-pillar. Although no robust technologies to implement large scale head-up-displays are available, a prototype to emulate a HUD-surface will be implemented.
- An augmented video stream on the display provided by a front-facing camera on top of the machine which indicates the deviation in height as an animation directly at the bucket.

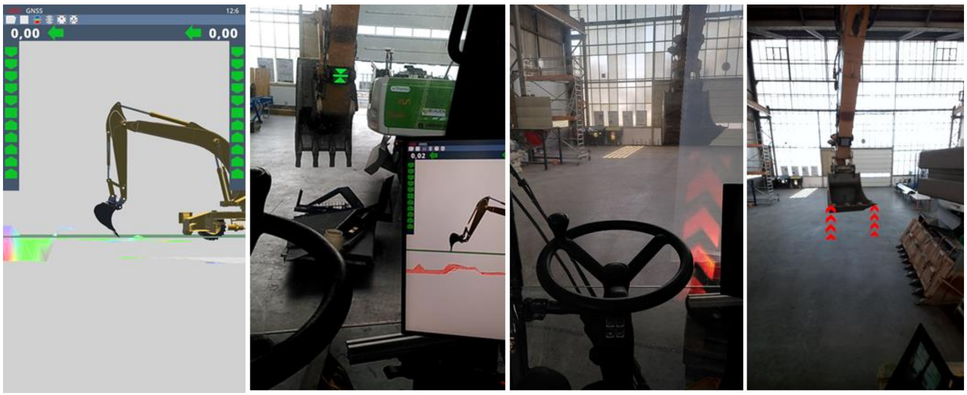


Figure 23: Different visualization options for UC3 scenario 1

For UC3-scenario 2 the following technologies will be implemented:

- Warning signals in case of a detected person in the danger area of the excavator will be presented in several feedback channels.
- Visualization of the position, distance and risk of collision for the detected persons in the VR-model of the excavator and surrounding on the main-display
- Visualization via light indicators in the cabin. This can be a light-stripes around the front window and around the main tablet.
- Visualization of a detected person on the LED-matrix panel as a symbolic indicator to raise awareness.
- Visualization of a detected person on the AR-window-projection

Figure 24: Different visualization options for UC3 scenario 2

For UC3-scenario 2, the following technologies will be implemented:

- Creating a reference between virtual machine and terrain design model and the real environment so that the operator is able to clearly see the correct alignment of machine, model and surrounding.
- Generation of a 2.5d-map to visualize the actual topography of the surrounding in the display based on the LIDAR-scan. The deviation to the target model can be highlighted e.g., with a heat map.
- Augmentation of a video stream of the front facing camera to visualize the proper alignment of model and terrain and the deviation in height across the whole working area.
- Texture Mapping of the 2.5d-map either by using a recorded image or even real-time-texture mapping
- Overlays of the target design in the VR-representation as well as in the AR-video feed.

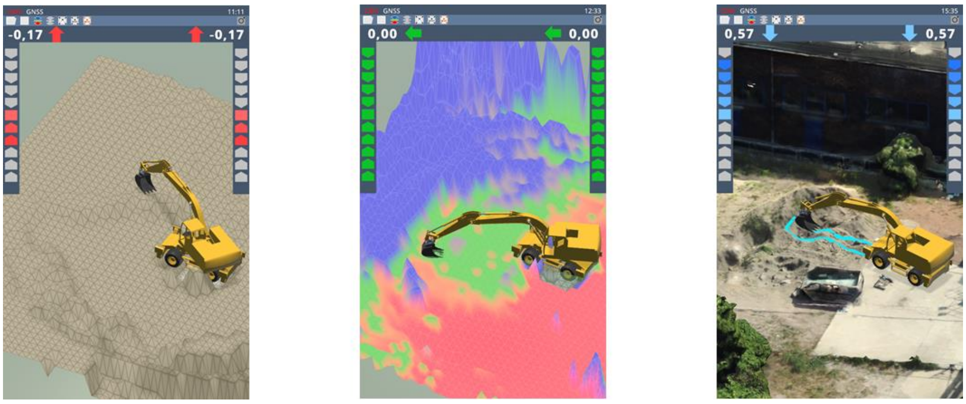


Figure 25: Different visualization options for scenario 3.

2.3.2 Integrated Technologies/Methodologies

2.3.2.1 Application of Co-Design Methodology in UC3

Due to the transdisciplinary co-design approach running in roughly the same way and timespan in all use-cases, this section will me mostly identical to 2.1.2.1, only deviating in dates and details of the process.

Following the user research conducted in Dresden and Glauchau, Germany, as part of T3.1, a problem scenario was defined (first step of the scenario-based design approach), describing a current typical excavator operation. This scenario was shared with the consortium. On October 20, 2023, an ideation workshop was held involving all active partners in this use-case. In this workshop, ideas for technology usage and some concepts already in development were collected and discussed in terms of their technical feasibility and expected utility for the operators. It was assumed that operators may have difficulties coming up with technology usage and interaction ideas on their own and may both over- and underestimate what is currently technically possible. Thus, the input from project partners was going to be implemented into a first activity scenario version, providing examples of how XR technology could realistically support operators at work and serving as a basis for the idea generation and validation with operators.
For explanations of the naming and background of realistic and futuristic vision scenario, see section 2.1.2.1.

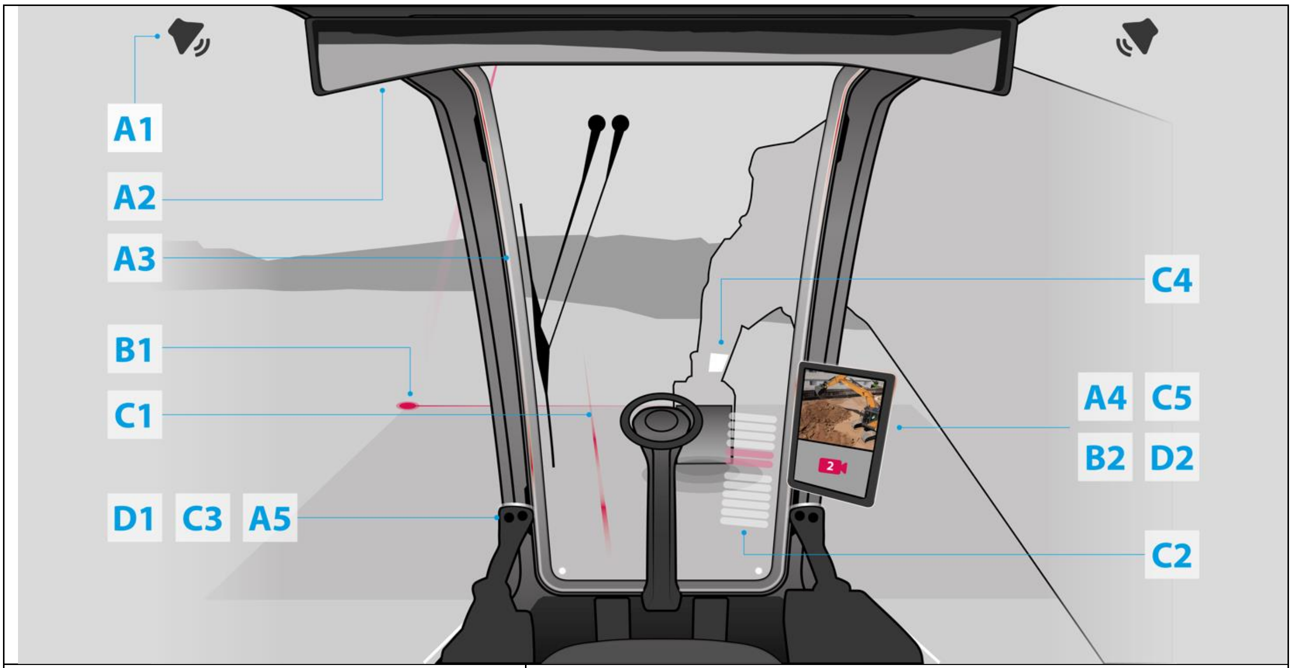
The first version of realistic and futuristic vision scenario for UC3 were completed and shared with the consortium in January 2024. Subsequently, the planning of co-design workshops with operators started in coordination with TUD and the ÜAZ Glauchau, a construction machinery training centre that had been acquired as supporting partner in summer 2023. The first stage of co-design workshops, focusing on validating and expanding planned technological features (e. g., usage of light bars for information visualization in the front window frame or laser projections of hidden structures into the construction trench), was completed in March 2024 (see Figure 26). The next stage of co-design workshops for UC3, aiming for validating and elaborating information design concepts, is expected to take place by the end of March 2024 as well. The validated information scenarios will provide input for more in-depth prototype design.

Figure 26: Picture from the visit to Glauchau in March 2024, where the first UC3 co-design workshops with experienced excavator operators and apprentices took place

After the development and validation of information scenarios, the final stage of the scenario-based co-design approach will be the creation of interaction scenarios, which also outline user interactions with the interface and the relevant outputs of the system. For UC3, possible dates for this stage still need to be arranged but may follow earliest in May 2024.

2.3.2.2 Information Requirements and multimodal interaction concepts

Also for UC3 HMI content analysis was conducted (see deliverable 4.1). This analysis revealed the importance of spatial information regarding the environment and the novel nature of virtual realities to be involved in future excavator HMIs. The resulting information range, high-level structure, complexity and importance of information informed a conceptual phase that defined HMI functionalities for UC3. This conceptual phase utilized our methodical approach of considering different information presentation modalities suitable for XR interaction (see deliverable 4.2), again resulting in a first version of the multimodal interaction concept for UC2 (see Figure 27).



A - 360° Object recognition		B – Work area planning	
A1	Surround audio	B1	Locate and visualize points and borders of pit with spot light, joystick control and touch control
A2	Back mirror		
A3	Ambient light feedback	B2	Manipulation dialog for pit model control
A4	Video augmentation	C- Relative surface profile (target profile and tool pos.)	
A5	External light feedback	C1	Offset to target height – projection
D – manipulation of virtual models		C2	Offset to target height – head-up display
D1	Switch real/virtual control through joysticks	C3	Depth/area limitation – joystick force feedback
		C4	Depth/area limitation – visual feedback matrix display
D2	Virtual 3D machine view	C5	Current and target surface profile (3D visualization)

Figure 27: Key visual of the XR HMI concept for use case 3 (excavator) including annotated functions

This concept focuses on the implementation of assistance systems, automated machine functions and ubiquitous connectivity, which are the key factors to leverage the productivity in the construction sector. Besides operating the machine, operators of excavators will face tasks like handling and manipulating digital models, controlling collaborating machine fleets as well as surveying and documenting the work results. Heterogeneous environmental influences, significant noise and vibration levels and a very busy surrounding with a high potential for accidents typically characterise the working conditions in a construction machine.

The XR HMI concept for this use case comprises of different augmenting information presentations that give the operator additional information about the presence and position of obstacles (A), tool position (B, C), pit design (B,C,D), and navigation and area restrictions (B,D) through different forms of augmenting feedback modalities (visual, acoustic and haptic feedback). This concept informs the following implementation of technologies and continues to explore and define their design visible to the human operator.

2.3.2.3 Identifying Privacy Requirements and Strategies for Mitigating Privacy Risks in Implementations in UC3

To identify the possible risks for privacy in UC3 and to start discussing a mitigation solution, we used the following technologies:

1. Series of questions in the semi-structured interviews [2] with the operators, performed in the frames of co-design workshops, conducted in the frames of T3.1. The questions for the semi-structured interview were developed based on an iterative design approach and followed the purpose of understanding end-users' perception of the data generated by the operation in terms of usefulness for their work and their will to share the data with external entities. The questions were also designed to understand the general privacy concerns of the operators and their perception of the future workflow, including the perception of the factors of automatization of the operations and new data modalities provided by XR. As the iterative process means

constant improvement and redesigning of the proposed solutions (in our case, a set of questions and sub questions) [3], the second round of the semi-structured interview with stakeholders is planned to be made in the start of Month 16. Also, as part of the iterative approach, we transformed the preliminary findings into practical privacy-related questions and integrated them into the realistic and futuristic scenarios described in 2.1.2.1. We plan to test them in the frames of a co-design workshop with operators in line with the timeframes, proposed in 2.3.2.1.

2. Based on the UC2 scenarios, finalized in D2.1, we developed a survey of privacy questions for the stakeholders regarding each of the proposed changes in the basic workflow, using the principles of Data Protection Impact Assessment[9]. The questionnaire helped identify the most privacy-critical parts of the proposed technology development and add privacy concerns to the discussion about the feasibility of proposed solutions.

3. Besides eliciting GDPR-related requirements, we applied the LINDDUN GO methodology [4] to elicitate a broader range of technical and non-technical privacy concerns from stakeholders. To do that, we organized one privacy workshop with representatives of UC3 and technological partners involved in UC33. We also used relevant results from the workshops of UC1, as these two UC share similarities in the developing solutions. The results helped identify the most privacy-controversial technologies with the proposals for mitigating the possible privacy risks.

2.3.2.4 Excavator Simulator

The Creanex Simulator platform starts with the core dynamic simulation, developed by Creanex in-house. It manages and controls all other components of the simulation.

The core dynamic solutions:

- Creates a dynamic scene that is the simulated world and everything in it. This scene consists of the world 3D model, any simulated objects, and the simulated machine.
    - The world 3D model, also called terrain, is a 3-dimensional map of the ground. It defines where ground level is in each position. The ground is static and can’t move or be affected by other simulated objects.
    - Simulation objects are representations of objects in the simulated world. They can for example be machine parts that make up the excavator, separate loose parts of the terrain such as loose rocks, or obstacles such as traffic cones and construction pipes.
    - The simulated machine can be driven and controlled in the scene. In this case, the machine is an excavator or a snow groomer (UC1). The machine consists of parts, and the kinematic configuration file determines the structure of the machine. Which part is attached to which part, in which position, and how can the parts move in relation to each other.
- Configures and runs the physics engine. The engine is deeply integrated into the dynamic scene, and the dynamic scene uses the calculations of the physics engine to update the positions and orientations of the simulated objects. The objects and the world have 3D models, which determine their shape in the physics simulation: what space they occupy in the scene and how they collide into each other. For a more detailed description, see Section 2.3.2.4.2.
- Receives and processes input from control devices, including the operator’s input, for example from joysticks.
- Transmits scene information to Unity Visual for graphics. Unity Visual has its own models for the scene and simulated objects. These visual models are graphics files that determine how the scene and simulated objects look. See Section 2.3.2.4.4 for a detailed description.
- Communicates with Python CrnxTesting and data interfaces. The simulator can send data of the state of the simulation and simulated machines to external devices.
- Displays data of the state of the simulation on various user interface windows. For example, a dialog that shows the position, orientation and joint angle of each machine part can be opened.

An overview of the individual components within the whole system is provided in Figure 28.

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[9] https://gdpr.eu/data-protection-impact-assessment-template

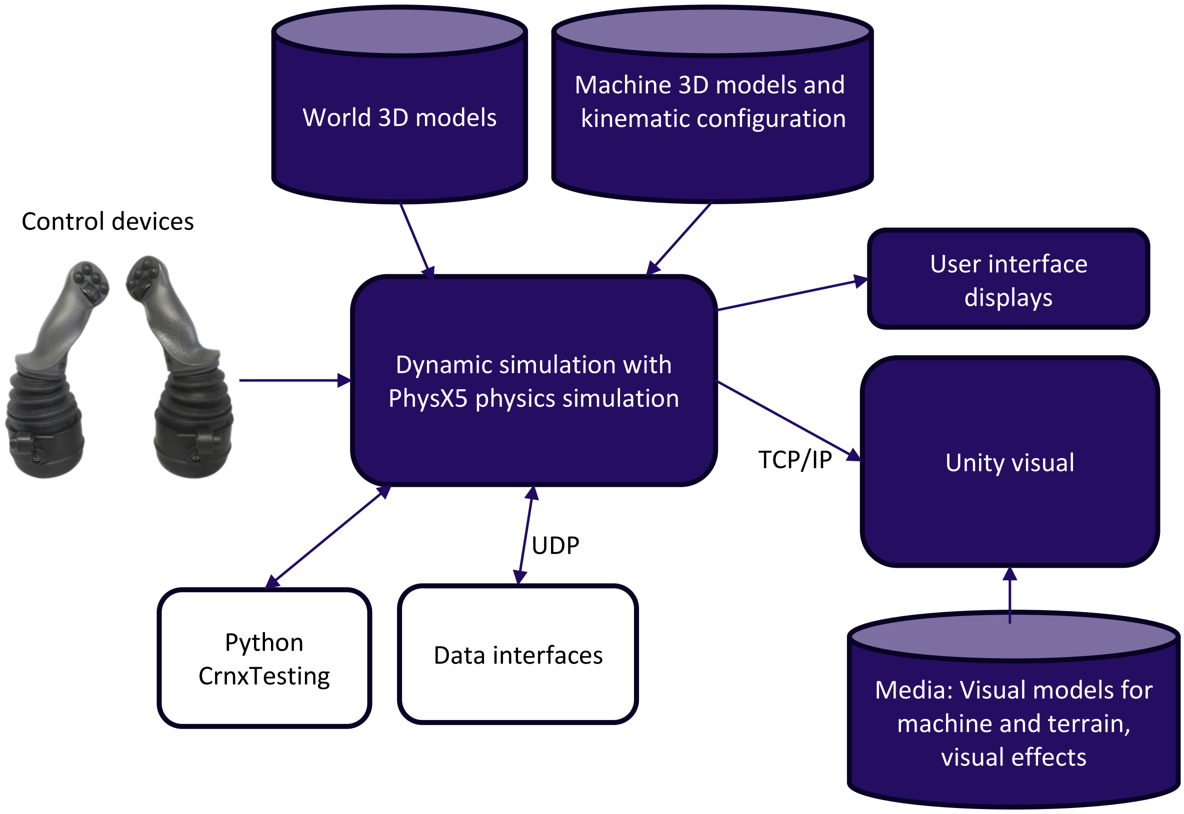

Figure 28: Creanex simulator platform components

2.3.2.4.1 Excavator Machine

Two different excavator machines are implemented in the simulator: a tracked excavator and wheeled excavator (see Figure 29). Each excavator has two different buckets that can be used with the machine: standard bucket and a RotoTilt bucket. The RotoTilt bucket can be rotated and tilted around its attachment point. Both buckets can be detached and then reattached during the simulation by the operator.

The ground can be dug and modified using the bucket. Excavated material can be moved and piled. The ground resists the movement of the bucket unless the bucket is aligned in a way that scoops up the material into the bucket.

The simulated excavator supports all the movements a typical real excavator would have. It can be driven around on its tracks or wheels, the upper body can be rotated around the carriage, and the boom can be operator with three different cylinders.

The operator can control the simulator machine with joysticks and pedals that are connected to the simulator. These control devices can be the same as in a real machine, or other similar joysticks. These devices send the control signals to the simulator using the CANopen-protocol. In collaboration with TU Dresden, the Danfoss JS1-H joysticks[10] for the excavator simulator has been successfully connected and configured.

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[10] https://www.danfoss.com/en/products/dps/electronic-controls/human-machine-interfaces-hmi/plus1-joysticks/js1-h/

Figure 29: Excavator digging ground

2.3.2.4.2 Physics Simulation

The physical dynamics of the simulator world, the excavator machine and other objects are implemented using the Nvidia PhysX5 physics engine[11]. The physics engine determines how objects behave when they interact with other objects and forces are applied to them. The physics engine maintains information of the object’s position, orientation, velocity, and momentum in the simulated world in real-time. The objects have shapes determined by their 3D collision models, mass and other properties, such as friction, rigidity, and restitution.

The excavator machine is simulated on the level of its individual moving parts and joints. The parts are connected to each other with simulated joints. These joints are defined in a machine configuration file, which determines how each part is positioned and can move in relation to other parts of the machine. The joints can be revolute and rotate around gives axis, or prismatic and move forwards and backwards on the configured axis. Stiffness and spring forces can be configured for joints. Stiffness is the resistance and defines the forces needed to move and drive the joint. Spring force is the force at which the joint tries to recover to its default position. Forces can be applied to the joints, causing them to move if the driving force is strong enough. The simulator system determines the direction and the magnitude of the forces applied based on the signals from the control devices. The physics engine maintains information of the forces and torques acting on each object, and this data can be collected and shown to the user (see Figure 30).

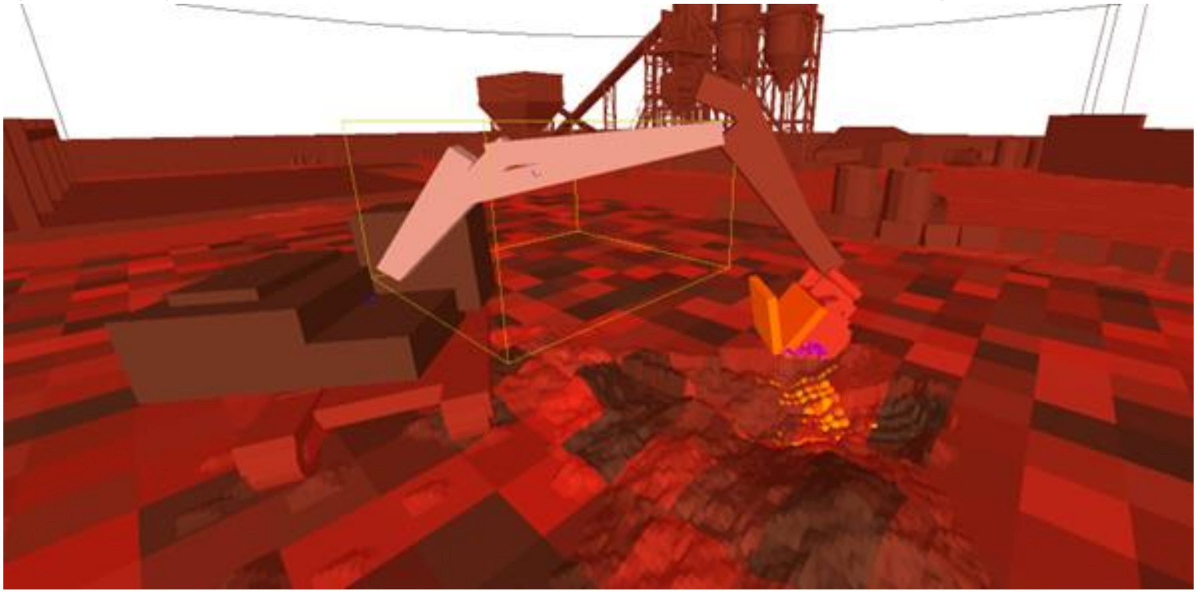

Figure 30: The physics engine’s internal representation of the parts of the machine, their shapes, and their ground.

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[11] https://nvidia-omniverse.github.io/PhysX/physx/5.3.1/index.html

Simulated joint sensors can be configured for each joint and IMU sensors for the parts, to measure positions, orientations, velocities, and joint angles of the machine parts. The simulator supports sending the sensor data over a CAN bus. The CAN messages are configured using the principles of the CANopen protocol and its device configuration files format.

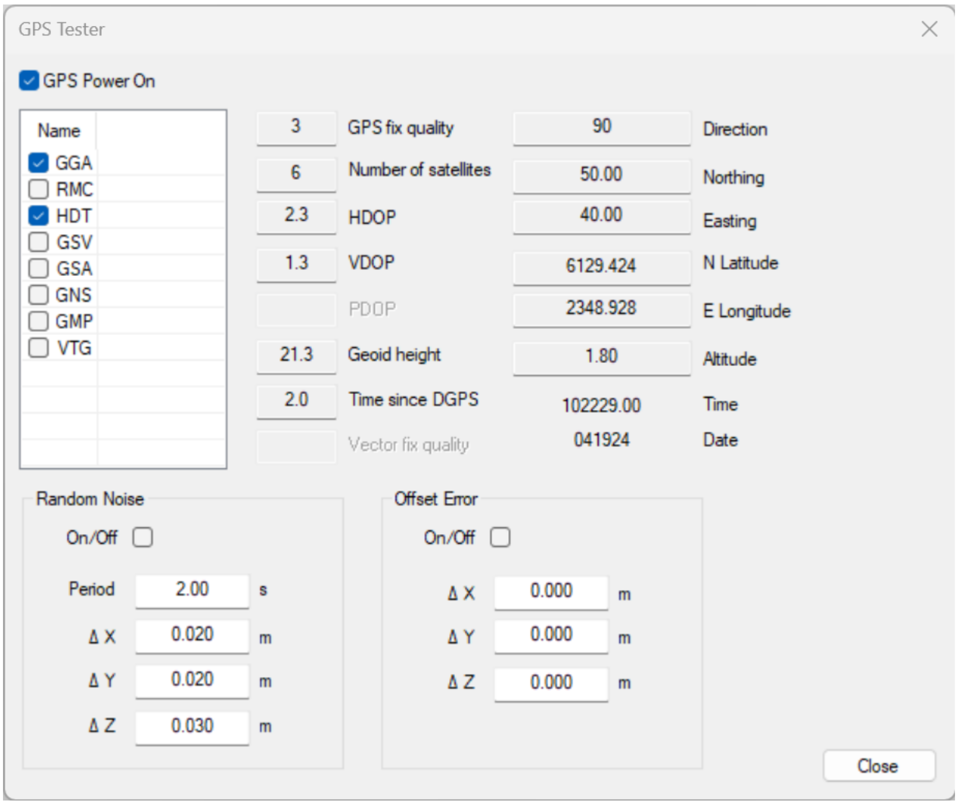
The joint's force measurements can be used to calculate the hydraulic power and efficiency of the machine. We are designing ways to visualize this for the operator, which would help the operator learn to use the machine more efficiently. The operator could be warned when some part of the machine is experiencing abnormally high forces, or when the operator is driving the cylinders in inefficient positions.

During this project, the physics engine used was upgraded from Nvidia PhysX 4.3 to PhysX 5.3. The newer version has less jitter and more realistic force measurements. Joint movements and long linked structures, such as the excavator boom, are more stable and accurate. Overall performance has improved, enabling higher framerate and more complex simulated world with a larger number of simulated objects.

2.3.2.4.3 GNSS Simulation

The simulated word uses its own local coordinates, but those coordinates can be mapped to WGS84 coordinates. The origin of the simulated world can be defined to be in some position in WGS84 coordinates, and then any other position in the simulated world position can be converted to WGS84 coordinates. This enables the system to simulate GNSS and give real-world coordinates to simulated objects.

A simulated GNSS device can be configured to any part of the machine to track its latitude and longitude. The simulator user interface has a special GNSS testing dialog (shown in Figure 31). The simulator can insert additional noise and offset to the GNSS data to simulate inaccuracies in measurement and calibration.



☑ GPS Power On

Name
☑ GGA
☐ RMC
☑ HDT
☐ GSV
☐ GSA
☐ GNS
☐ GMP
☐ VTG

3	GPS fix quality	90	Direction
6	Number of satellites	50.00	Northing
2.3	HDOP	40.00	Easting
1.3	VDOP	6129.424	N Latitude
	PDOP	2348.928	E Longitude
21.3	Geoid height	1.80	Altitude
2.0	Time since DGPS	102229.00	Time
	Vector fix quality	041924	Date

Random Noise
On/Off ☐
Period 2.00 s
Δ X 0.020 m
Δ Y 0.020 m
Δ Z 0.030 m

Offset Error
On/Off ☐
Δ X 0.000 m
Δ Y 0.000 m
Δ Z 0.000 m

Figure 31: GPS testing dialog

Creanex simulator supports multiple standard NMEA messages (GGA, RMC, HDT, GSV, GSA, GNS, GMP and VTG) and some manufacturer specific ones of Trimble and Leica (PJK, LLL and LLQ). The NMEA messages can be transmitted through either serial or ethernet connection.

2.3.2.4.4 Graphics Rending and Visualizations with Unity Visual

The visual view of the simulated world is made visible to the user by Unity HDRP. Unity HDRP is a rendering pipeline that takes a representation of the simulated 3D world and turns it into a 2D representation that can be shown on the simulator's displays. Each object in the simulated world is associated with a visual model that determines how the object will look. The visual model defines properties such as colour, transparency and a more detailed shape with triangle meshes. The object's visual model also can be given more complex properties for special effects such as light scattering, tessellation, and light emission[12].

The simulator can be used to make prototypes of different visualization technologies and evaluate how they would affect operating the machine. The simulator can be used to rapidly test and iterate different configurations, positions, and sizes for these visualizations. These effects are implemented in the simulator as visual effects in the Unity graphics engine. Figure 32 demonstrates marking areas and guiding lines to the sand surface. Figure 33 shows how an object partially underground can be highlighted and made visible to the operator.

Figure 32: Markers on sand surface

Figure 33: Underground obstacle highlighted in excavation area.

2.3.2.4.5 LIDAR and Laser Scanning

The Creanex simulator supports a virtual LIDAR, a laser scanner. The LIDAR works by sending many laser pulses to different directions around the scanner and measuring the distance at which the pulses hit an obstacle. This distance data forms a point cloud, which is a 3-dimensional model of the surrounding area and tells how far obstacles are detected and in which direction.

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[12] https://docs.unity3d.com/Packages/com.unity.render-pipelines.high-definition@17.0/manual/index.html

In the simulator, the scanner can be attached to any point in the machine, and the scanning direction and number of pulses can be configured. The resolution of the point cloud depends on the number of distance measurements. More measurements give a higher resolution but require more computing power or time.
The LIDAR can be implemented in the simulation either by using the visual depth buffer, or by using the object's shapes in the physis engine. The visual depth buffer method measures the distance to the object visual model and is done in the Unity graphics engine. The physics engine method measures the distance to the object's collision shapes in the physics engine representation, using PhysX tools (see Figure 34 and Figure 35).

Figure 34: Point cloud generated by simulated LIDAR compared to visual view. Distance data from Unity depth buffer. The LIDAR resolution is here 128x128.

Figure 35: LIDAR data visualized on top of standard visual view. Distance data from Unity depth buffer.

2.3.2.4.6 VR Video Passthrough to bring Real Objects into VR

The Creanex Simulator platform supports VR devices for display. VR goggles offer more immersive simulator experience than 2-dimensional TV displays. Using VR goggles, the simulated world seems truly 3-dimensional, the virtual world surrounds the operator entirely, and simulated objects appear to be their actual size. A drawback is that the operator loses all view to the real world outside when using VR goggles. This means that for example, they can’t see their hands on the control joysticks or any other part of their body.

One solution for this is video passthrough. The VR goggles have cameras taking video of the outside from the perspective of the user, and this video is shown inside the goggles on top of the simulated world. This enables us to bring real physical elements into the simulator worlds. A good use case for this is showing operators hands on the controller joysticks in the simulated excavator cabin.

We use VARJO XR3 headset that has video passthrough technology to implement this in our simulators. The positions of the joysticks are marked with a QR code the cameras in the headset can track. Then a video of the real environment around the QR code is brought into the virtual world. The video is displayed in a specified position in the virtual world, where the virtual machine's control joysticks and the operator's hand would be. Figure 36 demonstrates this concept. On the left is a normal picture of the control panel with joysticks. On the middle, they are brought into the virtual world, and on the right, the operator hands can be seen using the joysticks in the virtual world.

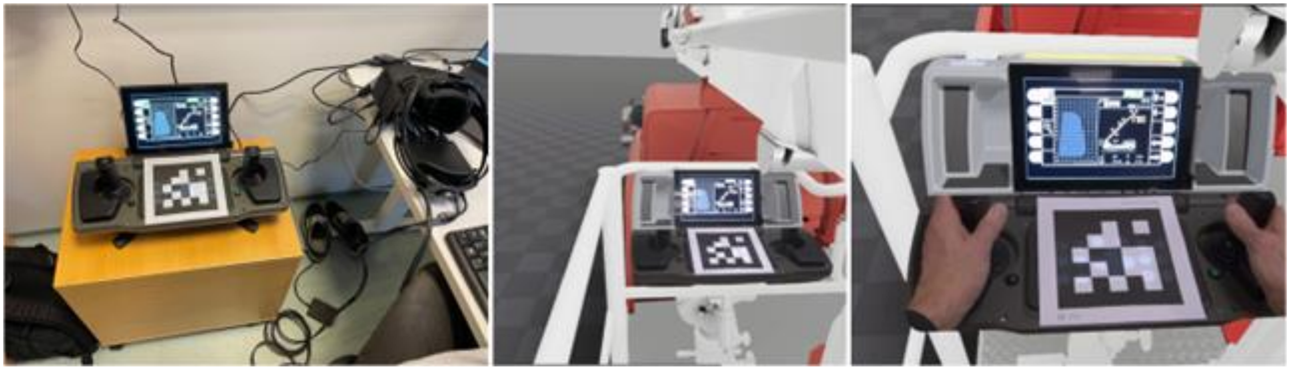

Figure 36: Demonstrator of brining control joysticks to simulated world using video passthrough.

This feature is not yet implemented in the excavator simulator but will be in the next stages of the project.

2.3.2.5 Data Handling and Processing Infrastructure

Similarly to the data handling and processing infrastructure for UC1 (snow groomer), the same approach will be applied for UC3 (excavator). The aim is to be able to process the majority of the data directly on the mobile machine and not being dependent on external computing resources.

The concept that is going to be applied in use case 3 is the same as the one in use case 1, so the information related to this can be read in Section 2.1.2.8. A schematic overview of the final integration within the excavator is depicted in Figure 37.

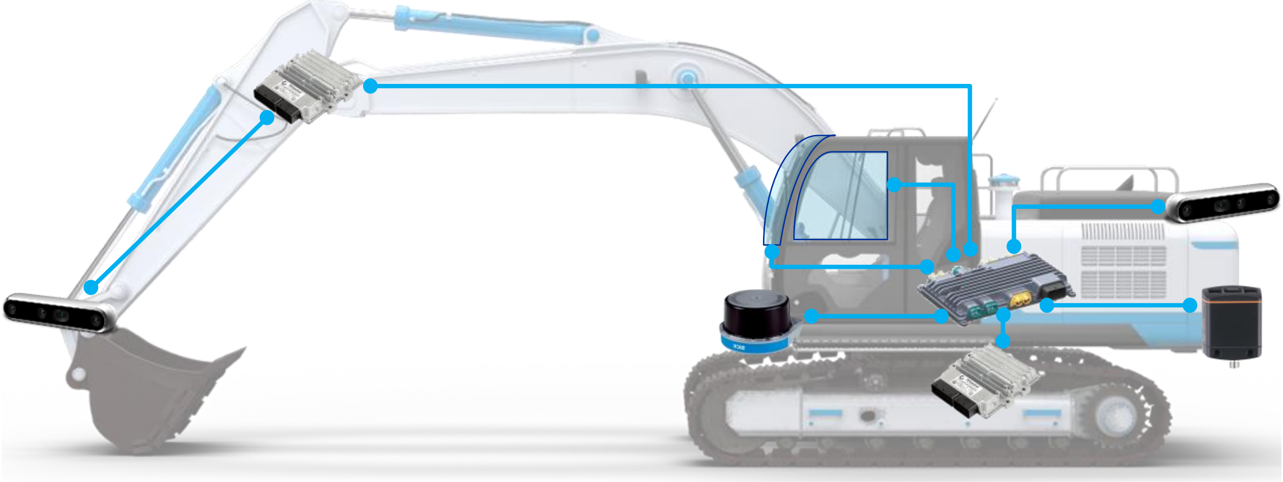

Figure 37: Schematic overview of integrated infrastructure into UC3 demonstrator

Similar as in use case 1, we will interact with the individual technology providers for this demonstrator and interface with the various sensors, actuators and output devices providers to merge them in the total infrastructure. For the final integration into the excavator, close interaction with partner TUD will take place.

2.3.3 Next Steps

Next steps are the implementation of the described visualization concepts and testing in the prototypic excavator setup. Therefore, the sensor interfaces, sensor data processing and graphical user interfaces must be implemented. Also, speakers for audio feedback, cameras for operator surveillance during testing, and actuators for haptic feedback in joysticks must be implemented in both standalone cabin and real machine. However, the data interface already exists. The standalone cabin will also get connected to a machine and environment simulation to provide immersive operation scenarios and real-time data for obstacle detection and machine behaviour. Both demonstrators will further be equipped with more functional versions of visual UIs for the terminal display that incorporates different augmented views but also a conventional overview on system parameters. The test setup will be completed with different setups of virtual mirrors via displays or projections. The demonstrator cab is meant as a playground to test different visualization concepts, especially light and display-setups. In expert workshops, different varieties of the XR-concepts are tested together with machine operators and HMI-experts.

3 Conclusions

This deliverable D6.1 provides an overview of the integration activities within the use cases that have already taken place or are planned to take place in the remaining time of the THEIA^{XR} project. The activities described in this deliverable are all related to the work required to integrate the developed technologies coming from WP3 – WP5. Some of the technologies are first tested in lab settings and additionally, first integration steps have also been taken without the actual mobile machinery. The experiences coming from the integration tests and from the demonstrations (which will be described in deliverable D6.2) will provide valuable input and feedback to the technical work packages and be the main source for updates to the technologies developed inside the project.

The deliverable describes the three use cases individually and highlights the integration activities for the technologies that will be deployed within the specific use case. It highlights the architectures for the different machinery and how potentially the individual methodologies (Co-Design and Privacy research) and technologies (e.g., 360° Lidar, simulation, computing infrastructure) will be applied and integrated. Some of the technologies are already integrated or some are still at a stage that they cannot be integrated yet, but the approach for integration is provided.

The plan for the project is to have a two-cycle approach, where in the first cycle (which runs approximately until month 18), the first prototypes are developed and potentially integrated into the machines. This deliverable focuses on the first cycle. The second and final art of the integration will be described in the second version of this deliverable (Deliverable D6.4), which is due in month M34 of the project.

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ABBREVIATIONS / ACRONYMS

AR	Augmented Reality
CAN	Control Area Network
DoF	Degree(s) Of Freedom
FOV	Field of View
GDPR	General Data Protection Regulation
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HMI	Human Machine Interface
HUD	Head-up display
IPC	Industrial Personal Computer
I²C	Inter-Integrated Circuit (bus)
LED	Light-Emitting Diode
LIDAR	Light Detection and Ranging
LINDDUN	Linking, Identifying, Non-repudiation, Detecting, Data Disclosure, Unawareness, Non-compliance
MCU	Micro-Controller Unit
NMEA	National Marine Electronics Association
ORTF	Office de Radiodiffusion Télévision Française
PC	Personal Computer
QR	Quick Reponse
RGB	Red, Green and Blue
ROS	Robot Operating System
RTK	Real Time Kinematic
RXRM	Real-Time Extended Reality Multimedia
SAR	Spatial Augmented Reality
SCL	Serial Clock Line (I²C bus)
SDA	Serial Data Line (I²C bus)
SPDT	Single-Pole Dual-Throw (switch)
SPI	Serial Peripheral Interface (bus)
UC	Use-Case
USB	Universal Serial Bus
VR	Virtual Reality
WP	Work Package

XR	Extended Reality