Grant Agreement N°101092861

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

## DELIVERABLE 6.5 – DEPLOYMENT, TESTING AND DEMONSTRATION OF THE THEIA-XR USE CASES (FINAL VERSION)

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| Author(s) | Daniel Röck (PRIN), Andrea Alesani (VTT), Timo Kuula (VTT), Kaj Helin (VTT), Thomas Howard (HAP), Pekka Yli-Paunu (KAL) |
| Contact details of the coordinator | Martijn Rooker, martijn.rooker@tttech.com |
| Internal Reviewer | Martijn Rooker (TTC)<br>Clemens Arth (TUG) [Affiliation] |

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# Executive summary

This deliverable presents the final deployment, testing, and demonstration activities conducted within T6.2 across all three use cases: snow grooming, logistics, and construction.
The development for the technologies and methodologies out of WP3, WP4 and WP5 are finalized and integrated.
The document details the deployment of advanced technologies on real mobile machinery as well as their implementation in demonstrator environments.
Compared to earlier phases, where solutions were primarily standalone, the final stage emphasizes full integration into operational systems to enhance operator support and safety.
Testing was performed under real-world conditions and through controlled demonstrator setups.
Each use case section includes a description of the testing and demonstration process, experimental scenarios, and lessons learned.

# Table of Contents



# List of Figures

# List of Tables



# 1 Introduction

This deliverable documents the final phase of activities within Task 6.2, concentrating on the deployment, testing, and demonstration of XR-based solutions for off-highway machinery. The primary objective is to finalize the integration and the demonstration of the technologies under realistic operational conditions.

Earlier stages focused on developing and evaluating individual components in isolation. In contrast, this phase emphasizes full system integration and end-to-end functionality. The solutions were implemented on actual machinery and demonstrator setups, enabling comprehensive evaluation in both controlled and real-world environments as described in D6.4.

Section 2-4 contains details on the deployment of XR-enabled systems on snow grooming, logistics, and construction machinery, the testing under diverse operational scenarios to measure usability and performance and the demonstration of the added value of XR technologies for enhancing visibility, reducing cognitive load, and supporting safe and efficient operations.

Lessons learned during these activities are summarized to guide future improvements and industrial adoption.

The last chapter of the deliverable provides a conclusion.

# 2 Use case 1 – Snow grooming

Snow groomer operations are restricted to the winter season, specifically during the months of December through April, and are contingent upon sufficient snow coverage—a condition that cannot be guaranteed. Consequently, the window for conducting field tests under real-world conditions is inherently limited. Given these constraints, deferring prototype validation to the final phase of the project posed an unacceptable risk, as only a few weeks would remain to integrate test outcomes into the deliverables. To mitigate this risk, we adopted a proactive strategy: utilizing the initial months of 2025 to perform real-environment testing with the technology available at that time, followed by subsequent evaluations using the demonstrator cabin. If feasible, a final round of field testing will be scheduled for December 2025.

## 2.1 Testing in real life environment

In autumn 2024, TUG delivered an enhanced thermal imaging system consisting of a single thermal camera integrated with a live video stream displayed on a tablet, designed for installation on a snow groomer. The primary objective of this technology was to provide operators with a thermal representation of their forward field of view via the tablet interface. Prinoth subsequently installed the system on a Leitwolf prototype vehicle (see Figure 1) and conducted extensive testing throughout the 2024/25 winter season. The evaluation involved 11 operators across four distinct locations, encompassing all operational scenarios, including winch-assisted grooming (see Figure 3).

During this period, the Leitwolf prototype was also deployed for the preparation of an Alpine Ski World Cup slope. This context offered a unique opportunity to assess the camera's performance in environments with multiple individuals in close proximity to the machine—a condition typically encountered only during major event preparations (see Figure 2).

**Figure 1: Installed thermal camera on a Leitwolf**

**Figure 2: Thermal camera showing persons, trees, nets, snow guns, skidoo and snow surface**

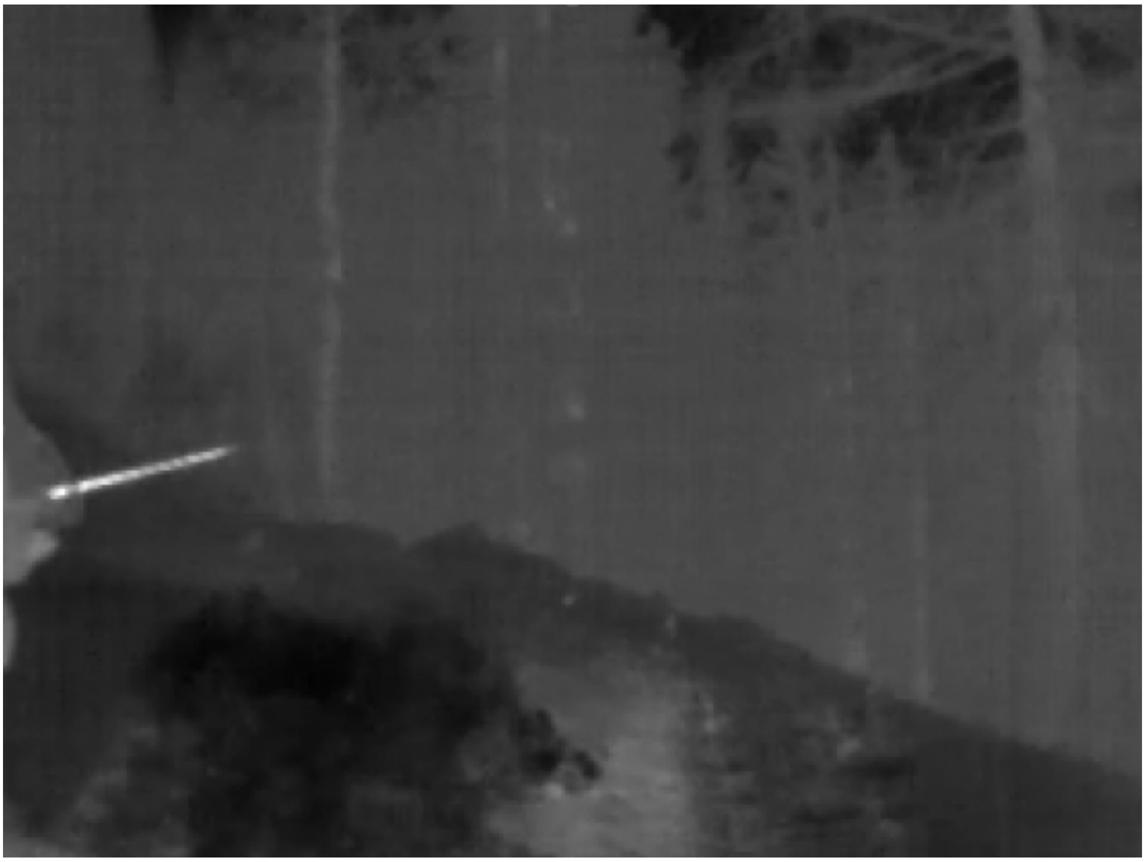


**Figure 3: Thermal camera showing winch rope, trees and snow surface**

A THEIA$^{XR}$ consortium meeting was convened during week 3 of 2025 at Prinoth's headquarters in Sterzing. The presence of all partners on-site provided an optimal opportunity to extend the meeting by one day to conduct technology integration activities (see D6.4) and perform field testing. Real-world testing was carried out over four separate days: the first two in January 2025 at Ridnaun (Italy, see Table 1 and Table 2) and the subsequent two in March 2025 at Ladurns (Italy, see Table 3 and Table 4).

| | | |
|---|---|---|
| Country: Italy | Test area: Ridnaun | Date: 14.01.2025 |
| Participants: TUG (3), HdM (2), TTC (2), PRIN (4) | | |
| Snow conditions: hard | Weather condition: few clouds/ clear | Ambient temperature: between 0 and -4° C |

**Table 1: first test day at Ridnaun**

| | | |
|---|---|---|
| Country: Italy | Test area: Ridnaun | Date: 15.01.2025 |
| Participants: TUG (3), PRIN (2) | | |
| Snow conditions: hard | Weather condition: clear | Ambient temperature: between 0 and -6° C |

**Table 2: second testing day at Ridnaun**

| | | |
|---|---|---|
| Country: Italy | Test area: Ridnaun | Date: 25.03.2025 |
| Participants: TUG (2), TTC (1), PRIN (3) | | |
| Snow conditions: Flabby, soft | Weather condition: few clouds/ clear | Ambient temperature: between 0 and +4° C |

**Table 3: third testing day in Ladurns**

| | | |
|---|---|---|
| Country: Italy | Test area: Ridnaun | Date: 25.03.2025 |
| Participants: TUG (2), TTC (1), PRIN (3) | | |
| Snow conditions: Flabby, soft | Weather condition: few clouds/ clear | Ambient temperature: between 0 and +4° C |

**Table 4: forth testing day at Ladurns**

Building on lessons learned from prior tests conducted in February 2024, all systems were thoroughly verified before deployment to Ridnaun. Preparations included ensuring the availability of the target surface model, configuring the Husky E-Motion with the snow measurement system, and implementing THEIA$^{XR}$ technologies on the roof-mounted support frame. The improved laser and projector systems were calibrated to achieve harmonized projections on the snow surface.

During these trials, it was observed that no localization signal was received from the CAN interface. Nevertheless, the available time was utilized to refine calibration and experiment with new projection patterns. The improved system demonstrated significantly enhanced visibility of projected figures on snow. These findings confirmed the necessity of a second testing phase.

**Figure 4: Impressions from Ridnaun**

Due to snow conditions in March, Ladurns was selected for the final test phase. By that time, previously identified issues had been resolved, enabling a successful setup. The first day focused on system configuration and functional checks. Additionally, a new target surface model was generated overnight to accurately reflect the snow conditions at the test site. On March 25, 2025, tests were conducted on laser and projector-based visualizations along a predefined path, as well as obstacle proximity warnings.

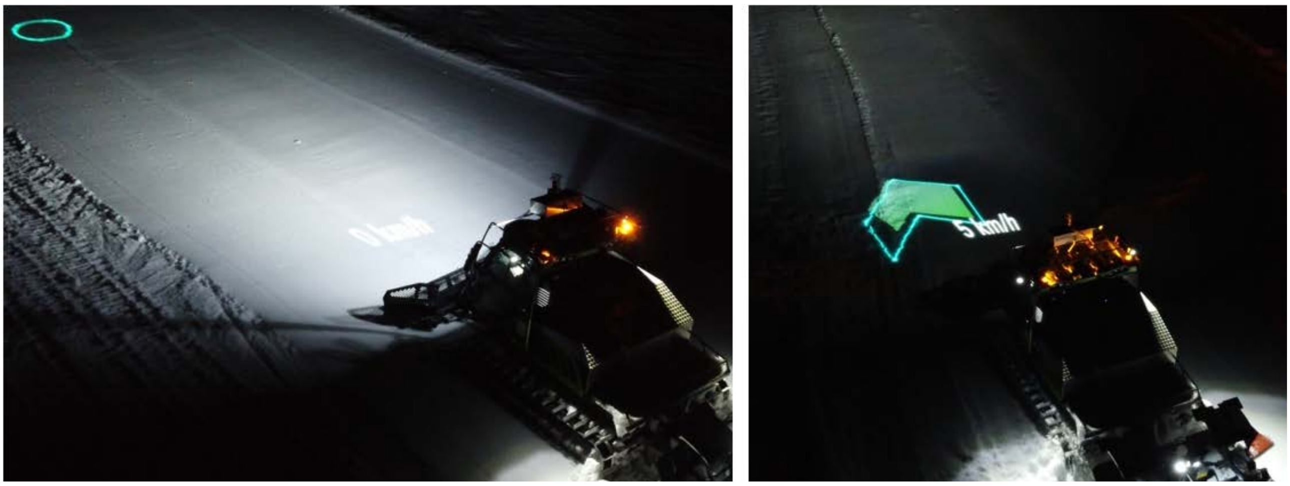



**Figure 5: Path projections onto snow**

Figure 6: Person proximity projection on snow surface

## 2.2 Testing with Demonstrator

### 2.2.1 InterAlpin trade fair

One of the main demonstration events in Use Case 1 was the InterAlpin trade fair, which is the main trade fair for alpine technologies and one of the most important ones for use case lead PRIN. The InterAlpin took place in Innsbruck, Austria from 20th until 23rd April, 2025. The planned goal for the demonstrator at the InterAlpin was to demonstrate results of the project, integrated into the cabin, to as many companies, interested people and operators as possible, targeting the snow grooming domain, where the InterAlpin turned out to be the perfect platform.

As was already mentioned in deliverable D6.4, a real snow groomer cabin was made available for integrating, testing and demonstrating technologies, before transferring them to the real snow groomer. During multiple integration meetings taking place at the premises of partner PRIN, the main focus was on getting all the components integrated into the cabin and interacting with each other. Additionally, multiple functionality tests have taken place in the manufacturing halls of partner PRIN, where the demonstrator was located. These integration tests were performed together with technical people of PRIN, but also with people that are operating snow groomers, providing valuable feedback to the different technologies. By combining the different technologies into the cabin, the development team enable operators to experience a virtual world (a skiing slope) with XR technologies that made it possible to provide information to the operators regarding aspects that are not directly in their field of view. In total, two large integration meetings and some smaller ones have taken place before the InterAlpin trade fair.

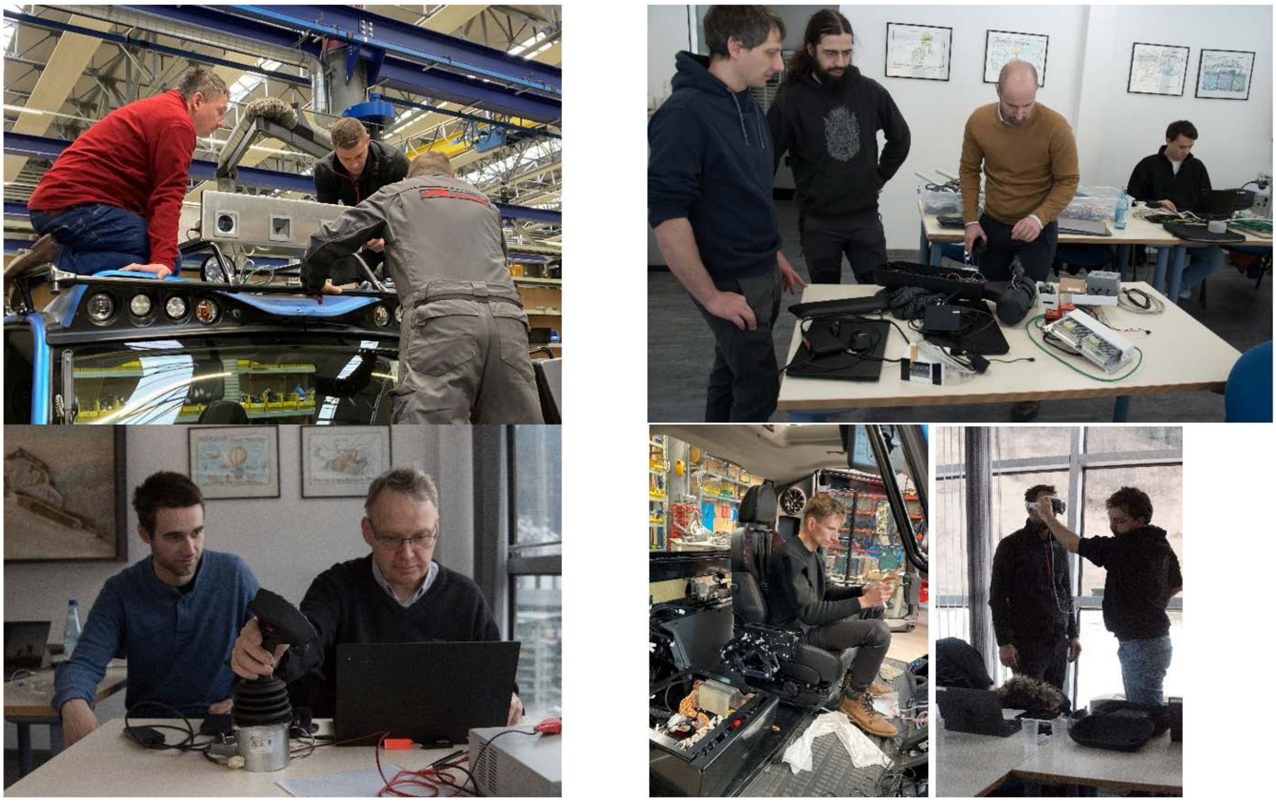


**Figure 7: Integration and testing activities for the snow groomer cabin**

The demonstrator (depicted in Figure 7) consists of:

- Snow groomer cabin
- Central processor acting as data handling and interaction infrastructure
- Virtual world of a skiing slope, where the virtual snow groomer is driving around
- Active lightning, using LED informing the operator if skiers are coming from sides that are not visible to the operator
- Track controllers, controlling the virtual snow groomer
- Joystick, controlling the virtual blade of the snow groomer

Already during the integration phase, many functionality tests have been performed while integrating the individual solutions into the cabin, to ensure that the technologies are operating the way they are planned.

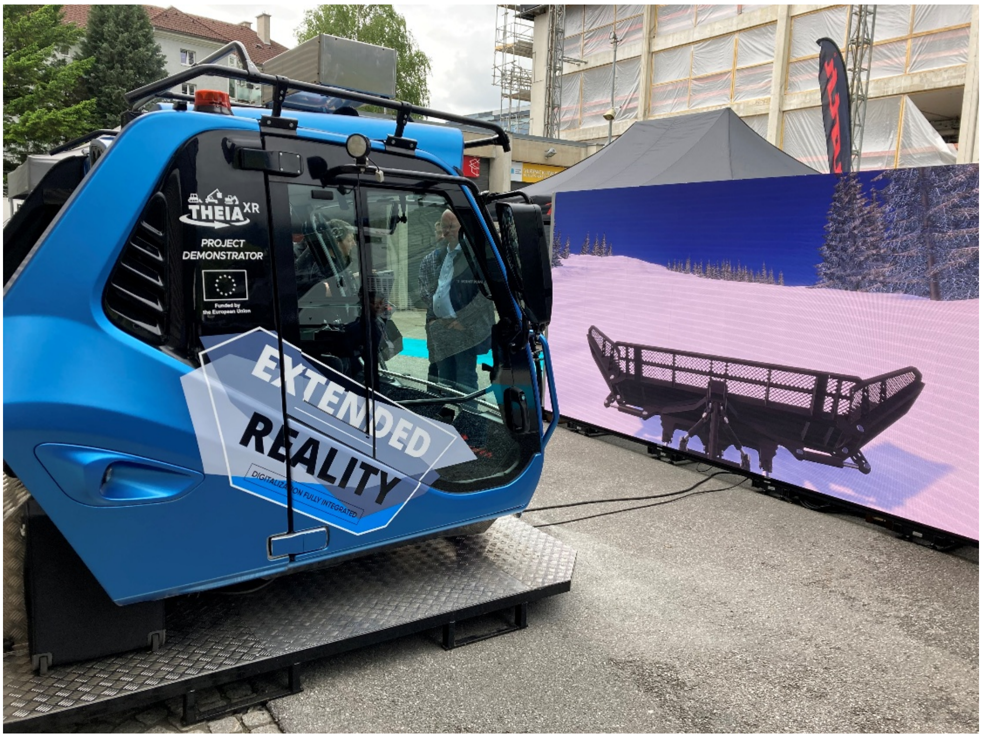



**Figure 8: InterAlpin Demonstrator**

The goal of the InterAlpin was to demonstrate the results of the project to a larger audience, including OEMs, system integrator, but also to operators of snow groomers. This is one of the main advantages of the InterAlpin trade fair, as a large selection of snow groomer operators are visiting it and want to experience new technologies for snow grooming.

**Figure 9: Interior of demonstrator, with operator seat, central processor, and operators working with the demonstrator**

During the event, we had many people visiting our demonstrators (see Figure 10), enabling us to interact with many operators, but also companies and/or institutes from outside the consortium. These people provided us with valuable feedback with respect to usability, applicability, usefulness, but also regarding societal and ethical considerations.


Figure 10: Interaction with operators at the InterAlpin 2025

An additional note to this demonstrator, as it will also be displayed at the UnitedXR conference in Brussels, from 8th till the 10th of December.

### 2.2.2 Haptic track controls unit

Because of technical issues encountered with the Central Processing Unit, Haption redesigned a direct interface between the Haptics ECU and the Creanex Simulator, which controls and reads data from the simulation environment over a UDP socket, and implements the communication protocol described in deliverable D5.3 "Visualization and interaction infrastructure" to relay information to and from the Haptics ECU. Because this simplifies the overall configuration procedure for the haptics functions, it also allowed for implementation of a configuration file, allowing easy update of the haptics functions parameters during testing. Thanks to this, it was possible to successfully drive the simulated vehicle using the novel haptic track controls (see deliverable D5.6 "*Multimodal Immersive Cockpit (final version)*" for hardware details). The first concepts of vibration feedback for skier proximity, vibration feedback for off-lane deviation, as well as force feedback assistance for braking in case of skier proximity could be tested (see also deliverable D4.8 "*Interaction concepts (final version)*" for details on these feedback functions).

#### *2.2.2.1 Vibration feedback for skier proximity*

The concept to inform operator about the presence, distance to, and heading towards obstacles in the vicinity was deemed to have some flaws: vibration feedback would alternate between the left and right stick handles, with a period proportional to the distance of the approaching skier. This would give a clear idea of skier distance, but not of skier position relative to the snow groomer. We therefore iterated on the concept, dividing the space around the snow groomer into three regions.

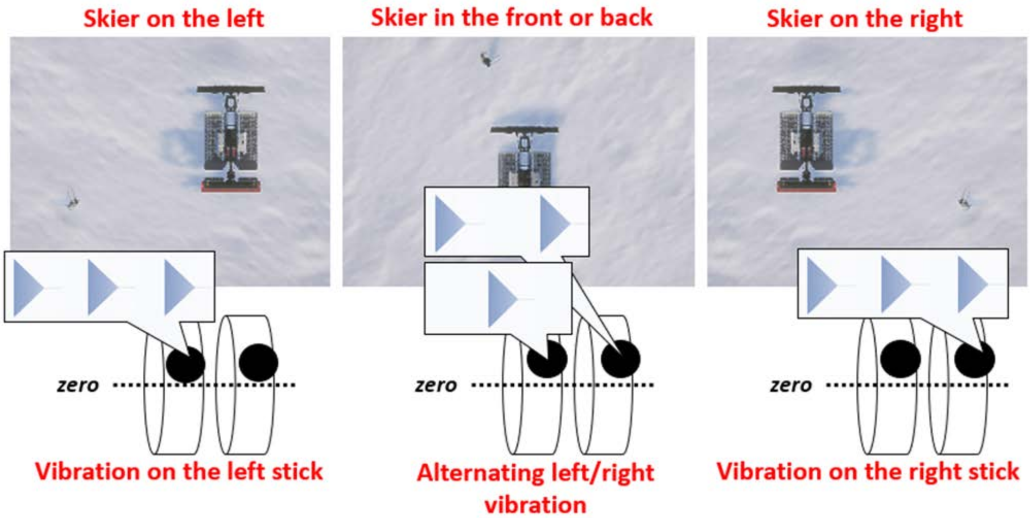


Figure 11: Improvement made to the skier proximity warning vibration feedback

For skiers located directly in the front or back of the vehicle now trigger alternating vibrations as they did initially (centre in Figure 11), however skiers on the left or right of the vehicle trigger vibrations exclusively on the left or right sticks exclusively (left and right in Figure 11). The vibration period calculation scheme remains unchanged. The vibration pattern (250Hz sinusoid for 0.2s) was also changed to a lower frequency (110Hz), as this increased cue saliency and was deemed to better convey urgency and a sense of risk inherent to the situation where a skier approaches the vehicle.

#### *2.2.2.2 Force feedback braking assistance for skier proximity*

The concept to inform operator about the presence, distance to, and heading towards obstacles in the vicinity was deemed adequate, however it led to an issue specific to the virtual testing environment. Indeed, inside the snow grooming simulation, when skiers come within 10m of the vehicle they would stop. At this lower threshold distance, the force feedback would drive the sticks to the zero position, preventing the operator from moving the vehicle away from the skier, thus putting the system into deadlock. To mitigate this issue and make the system more usable in situations where an operator needs to navigate away from a skier, we adapted the force feedback algorithm as follows:

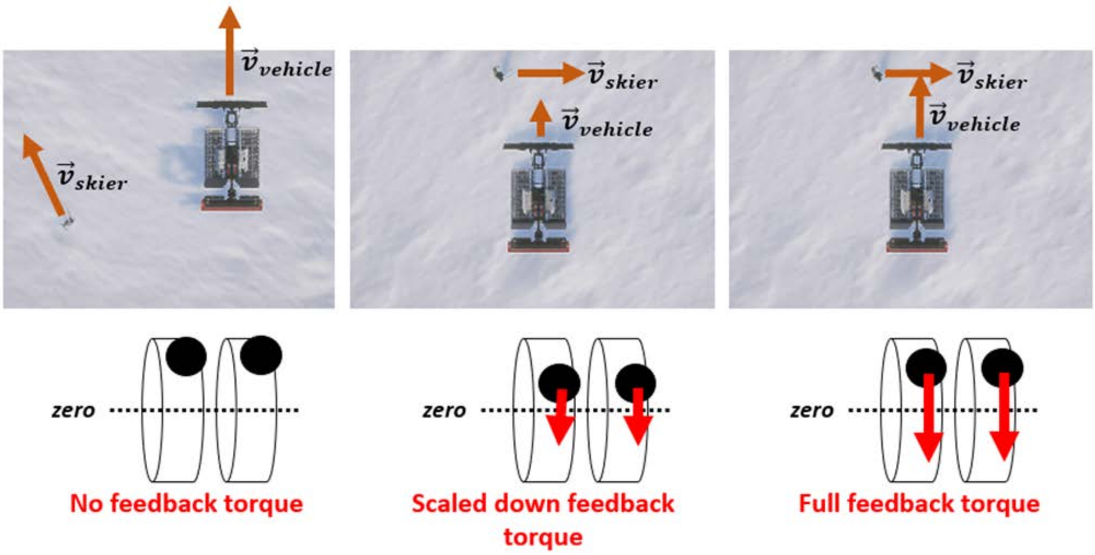


Figure 12: Improvement made to the skier proximity torque feedback function

Instead of simply applying a torque inversely proportional to the distance between skier and vehicle, we compute the derivative of the distance between skier and vehicle (i.e., the relative approach speed). If this derivative is positive (vehicle and skier moving away from one another – left in Figure 12), no torque is applied. If this derivative is negative but has a magnitude below an admissible approach velocity – centre in Figure 12), torque is applied but with a scaling factor < 1 applied, providing information to the operator without hindering operation. Otherwise, full resistive torque is applied as originally designed (right in Figure 12), implementing the safety function to its full extent. This allows the operator to slowly manoeuvre around skiers, at a speed allowing both parties to easily react to any danger, while preventing any collisions or manoeuvres at a dangerous speed close to skiers.

#### *2.2.2.3 Vibration feedback for off-lane deviation*

This feedback function to inform operator about vehicle width and alignment relative to trajectory, targets, slope and horizon line and the feedback function to "Safe path home" guidance was deemed adequately designed from the get-go and thus tested as-is.

### 2.2.3 Simulation

Following the latest update of the simulation platform by Creanex, several operator-requested functionalities were integrated, significantly enhancing the demonstrator's operational value. The update introduced a rear-view perspective, a 360° top-down view, dynamic snow movement visualization, a blade position indicator bar, and a target surface indicator bar. Additionally, a path predefinition feature was implemented, enabling the projection of directional arrows along a predefined route to provide real-time guidance to the operator.

**Figure 13: Simulation with rear view, 360° top view, blade indicator bar and path projections**

### 2.2.4 Testing at Prinoth

The same demonstrator cabin presented at InterAlpin was subsequently utilized at Prinoth's headquarters for operator testing. In this setup, a large display screen replaced the LED wall used previously. For the final testing phase, an extended version of the system with additional functionalities, described in Sections 2.2.2 and 2.2.3, was available. Operator testing was conducted during the last week of July and mid-October.

Prior to these sessions, detailed task definitions and environmental conditions were established for each use-case scenario, aligned with those specified in Deliverable D2.4. This ensured consistency in evaluation and facilitated systematic assessment of the enhanced functionalities.

In the first scenario, operators were tasked with redistributing snow within a designated area to achieve the predefined target surface (see Figure 14 - Figure 16).

**Figure 14: Target area with snow to be removed and indicator of blade position vs target position**


Figure 15: Indicator overlapping between blade position and target position


Figure 16: Partially finalized task to reach target surface

In the second scenario, operators were instructed to follow a predefined path within a designated area, performing multiple repetitions with the objective of avoiding collisions. During this task, haptic feedback was provided through the track controls, complemented by visual cues from the LED bar integrated around the windscreen (see Figure 17and Figure 18).

**Figure 17: Operator performing the task trying to avoid obstacles**

**Figure 18: Cabin setup with haptic track controls**

In the third scenario, a complete whiteout condition was simulated to evaluate operator performance under severely reduced visibility. THEIA$^{XR}$ technologies were employed to guide the operator along a predefined path toward the designated target position. Assistance was provided through visual projections on the snow surface in front of the vehicle and haptic feedback via the track controls (see Figure 19).

Figure 19: No view scenario with projected arrow guidance

## 2.3 Conclusion and lessons learned

The technologies were validated under real-world conditions and within the demonstrator environment to assess functional performance and usability. Initial concepts underwent iterative refinement throughout the project, with a strong emphasis on robustness and operator-centered design. Continuous interaction with professional operators and domain experts was essential to address concerns and incorporate feedback into successive development stages.

The integration of advanced technologies and optimized visualization strategies demonstrated measurable improvements in operational efficiency and user experience. The evaluation confirmed that combined functionalities deliver significantly greater benefits compared to isolated solutions. These findings underline the potential for further development, particularly in enhancing multimodal interaction and improving system reliability under diverse operational conditions.

The final phase of the project successfully demonstrated the deployment, integration, and testing of advanced operator-assistance technologies in real-world environments and within a controlled demonstrator setup. Compared to earlier stages, where solutions were primarily standalone, the integrated approach provided significant improvements in usability, robustness, and operational efficiency.

Field tests across multiple scenarios —snow redistribution, collision avoidance, and whiteout navigation— validated the effectiveness of multimodal guidance systems combining visual projections, haptic feedback, and enhanced operator interfaces. Simulation updates and demonstrator-based evaluations further confirmed the value of immersive visualization and predictive guidance functionalities.

The results indicate potential for further development and industrial adoption. Future work should focus on extending functionality, improving system robustness under extreme conditions, and exploring cross-domain applications beyond snow grooming

# 3 Use case 2 – Logistics

## 3.1 Testing in real life environment

The final test for UC2 integration was conducted in Ljungby, Sweden, on Sep 25th - 26th at Kalmar's research premises. The planned agenda divided the work on the two days as following: on the first day, a first installation would be attempted and tested on the machine in an indoor setting, in order to assure that all the components are reachable and can communicate with each other over the local network. On the second day, the focus would shift towards running the system outdoor in a real operations scenario. On top of everything tested on the day before, the computer vision and localization algorithm would be tested with direct sunlight, and a remote connection would be tested first from Ljungby's control room and eventually to Tampere's powerwall display (where the reach stacker simulator was also tested).

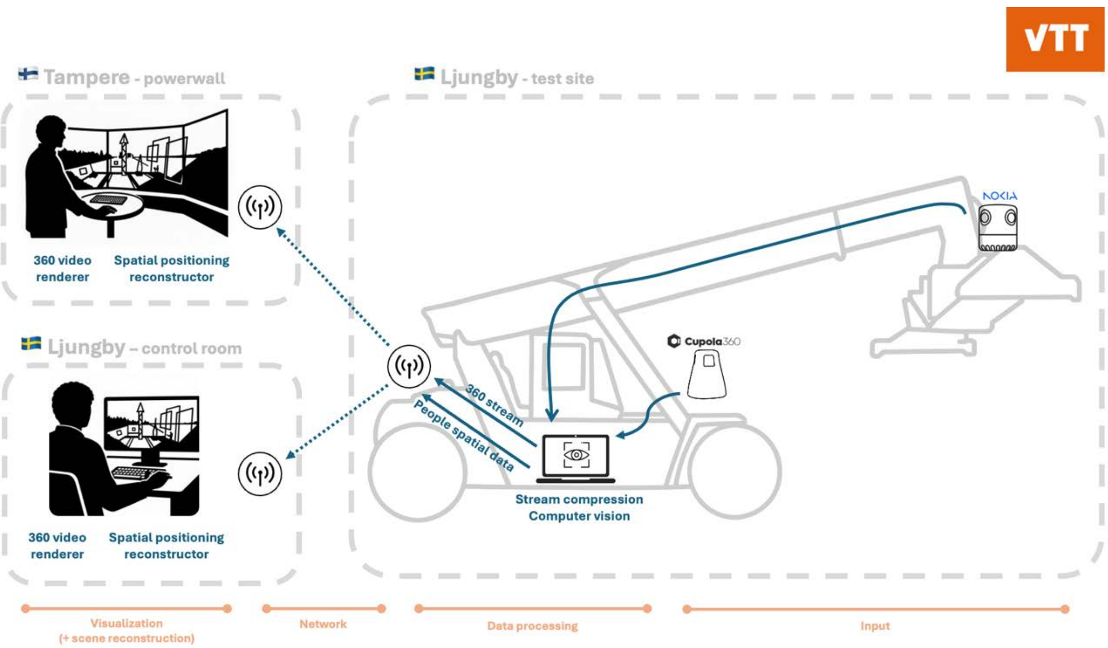



Figure 20: High-level information flow architecture.

### 3.1.1 First day / indoor installation

The testing setup includes:

- Nokia360 camera
- Cupola360 camera
- Switch (with PoE for Cupola360)
- Router for mapping local camera addresses
- 5G hotspot for remote connection
- Dedicated PoE for Nokia360
- Ubuntu 22 LTS laptop for RXRM connectivity
- Windows 11 laptop running VTT's computer vision and digital twin software
- Windows 11 / macOS laptop running the Unity application to visualize the scene from a remote location

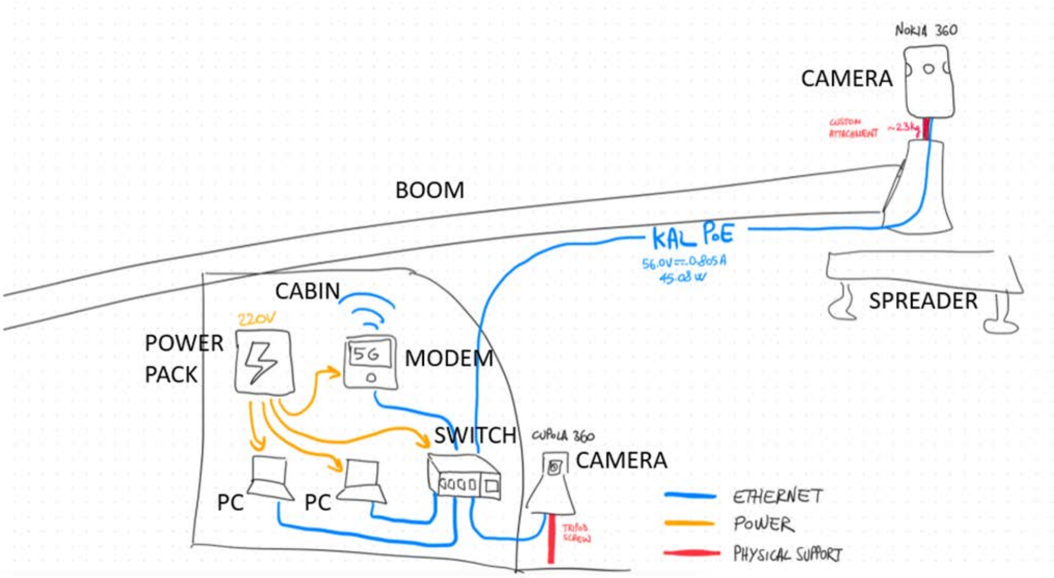



**Figure 21: Initial draft of the setup schema for the hardware components on the reach stackers.**

For the sake of simplicity, the final setup was not inside the cabin but on the side of the reach stacker, as can be seen on Figure 22. The setup was designed to give us solid coverage of the reach stacker's working environment, whether we wanted to monitor things live or look back over what had happened. By combining different types of cameras and networking gear, we aimed to make it possible for all the visual data to sync up and be accessed from several viewpoints. With dedicated laptops running the main software, the system promised to handle complex scenarios and allowed remote users to interact with the digital twin from anywhere.

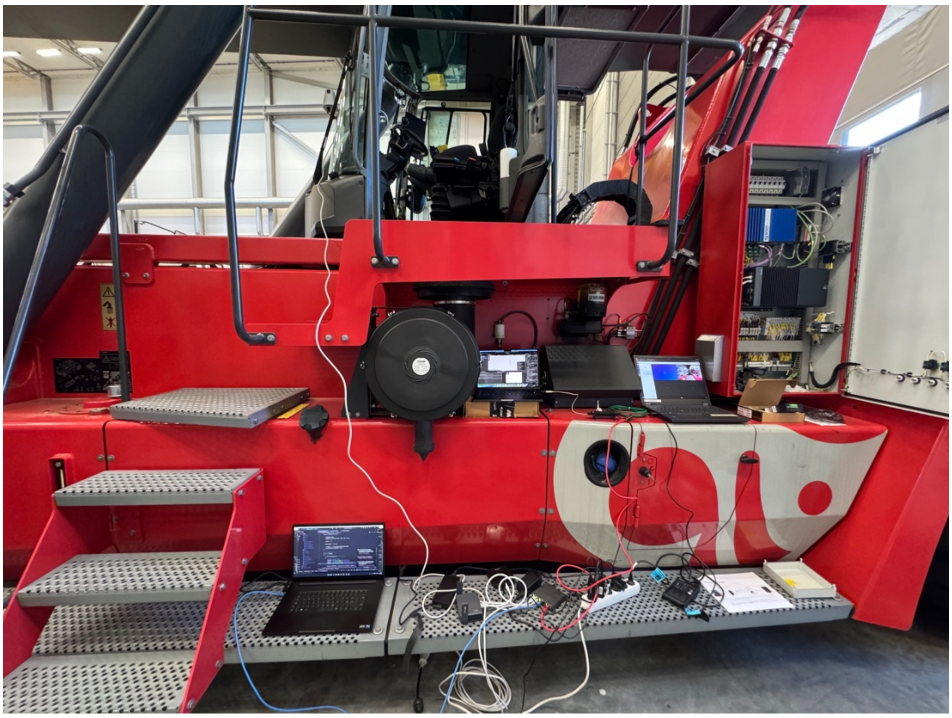


**Figure 22: The tested setup for this remote viewing solution.**

The Cupola360 camera was mounted directly onto the cabin's windshield using a reliable suction cup, streamlining the setup process. In parallel, the Nokia360 was positioned at a higher elevation on the spreader to capture an alternative viewpoint. Since the Cupola360 offers approximately 75 degrees of vertical coverage, careful consideration was required for placement. This arrangement ensured both cameras recorded sufficient action without the risk of missing key footage.

**Figure 23: Nokia360 camera is mounted on top of the spreader, while Cupola360 was placed on the cabin's windshield.**

Personnel from Ljungby's facility helped us setup the cameras on the vehicle and connect them with Power-over-Ethernet (PoE) cables to our computing devices. Nokia 360 camera was the only device powered directly from the reach stacker's battery system. A separate socket available in the workshop was used to power the PCs, as well as the Cupola360 camera, the switch, the router and the 5G hotspot.

**Figure 24: Personnel from Kalmar mounting the Nokia 360 camera on top of the reach stacker's spreader.**

At the end of the first day, the system showed to be working correctly. Both cameras were powered on and reachable by the Nokia RXRM laptop server. VTT's computer vision PC could also correctly retrieve video footage and reconstruct a 2D map of people around the reach stacker. The cameras did not even need to be recalibrated from the lab configuration (where they were tested for about 160cm from the ground, which is way lower than the about 350cm where they were placed for the testing). This gave some error for the people distance estimation, but way lower than expected and overall acceptable to test the usability of the system. By the end of the first day of testing, the integrated system proved that it functioned as expected. Both the Cupola360 and Nokia360 cameras were powered up and stayed connected to the Nokia RXRM laptop server throughout the evaluation. The VTT computer vision software, running on a dedicated PC, was able to capture and process video streams from both cameras, which allowed for real-time reconstruction of a 2D map showing where personnel were around the reach stacker. The move from lab conditions to the real test environment went smoothly—there was no need to recalibrate the cameras, even though their mounting height increased considerably (from about 160 centimetres in the lab to roughly 350 centimetres on the actual machine). This change led to only minor differences in how the system estimated distances to people near the vehicle. The errors in these distance calculations were much smaller than expected and didn't impact the usability testing.

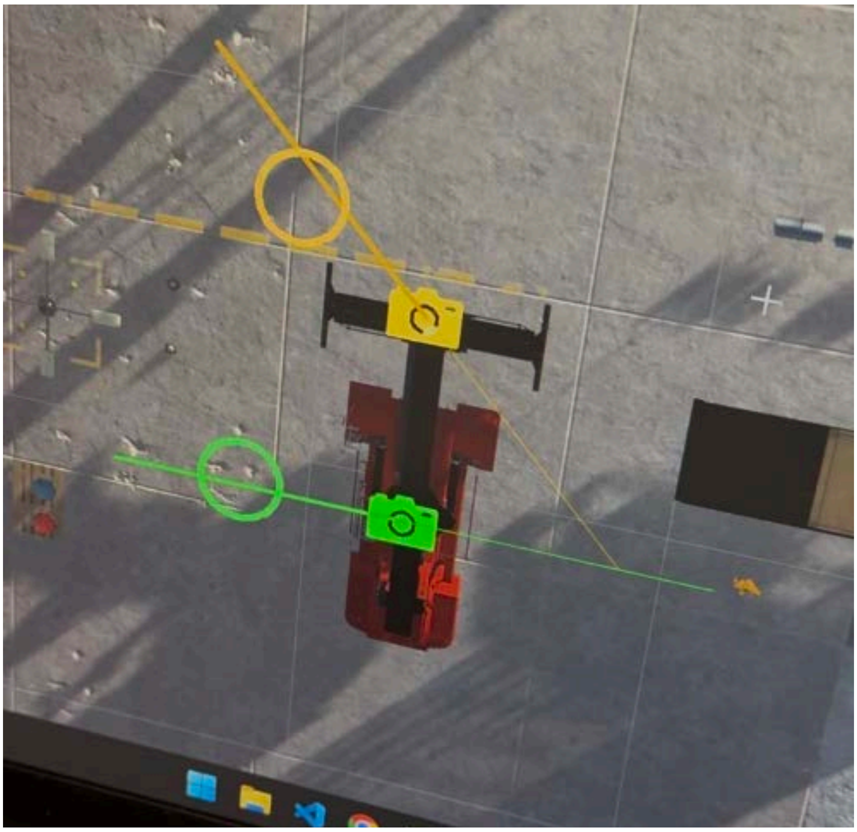


**Figure 25: The application elaborates detections from both cameras (Cupola, in green, and Nokia, in yellow) and places them on a 2D map of the reach stacker.**

### 3.1.2 Second day / installation in actual outdoor test field

The second day focussed more on the testing of the integrated system on the field. The reach stacker was moved to the outdoor test yard, and a container was later placed right in front of it to simulate a realistic scenario. Once the reach stacker had been relocated to the outdoor test yard, we set about arranging the rest of the test setup to mirror a typical working environment as closely as possible. To add an extra layer of realism, we brought in a container and positioned it directly in front of the machine, just as you'd find in an actual operational scenario. Having the container in-situ meant we could properly check camera angles, run through various monitoring tasks, and generally get a feel for how everything functioned when the equipment was outside, exposed to real-world conditions.

Figure 26: Group picture with the reach stacker in the outdoor test facility. From the left: Pekka, Martijn, Andrea, Kaj.

Setting up outside required full disassembly and reassembly. The process demanded careful attention to each component, ensuring everything was working correctly before restarting operations. An external battery kept the reach stacker powered, even as temperatures dropped, and a cord extender supplied electricity to devices that needed it for proper functioning. Nokia's RXRM laptop had a kernel panic on its first boot—possibly due to cold or electromagnetic devices—but after a few troubleshooting steps, it was resolved. After moving the reach stacker to the outdoor test yard, all the hardware had to be redeployed. A power generator was used to keep the reach stacker's battery running, while a power extension reel connected the computing hardware to electricity (see Figure 27).


Figure 27: Reach stacker at the outdoor test yard

The outdoor setting gave us a clear view on how the UI looks like in a realistic setting. The main features shown in this field-test are the load chart visualization and the highlight of people, even when occluded by an object. The load chart UI allows operators to see the container's distance and the vehicle's tipping risk. A blue square marks the container's position on the chart, although during this test it wasn't updated in real time due to missing CAN bus connection to the reach stacker (see Figure 28). On the other hand, the people highlight UI literally makes "the invisible visible" by leveraging the digital twin reconstruction of the scene from different camera angles.

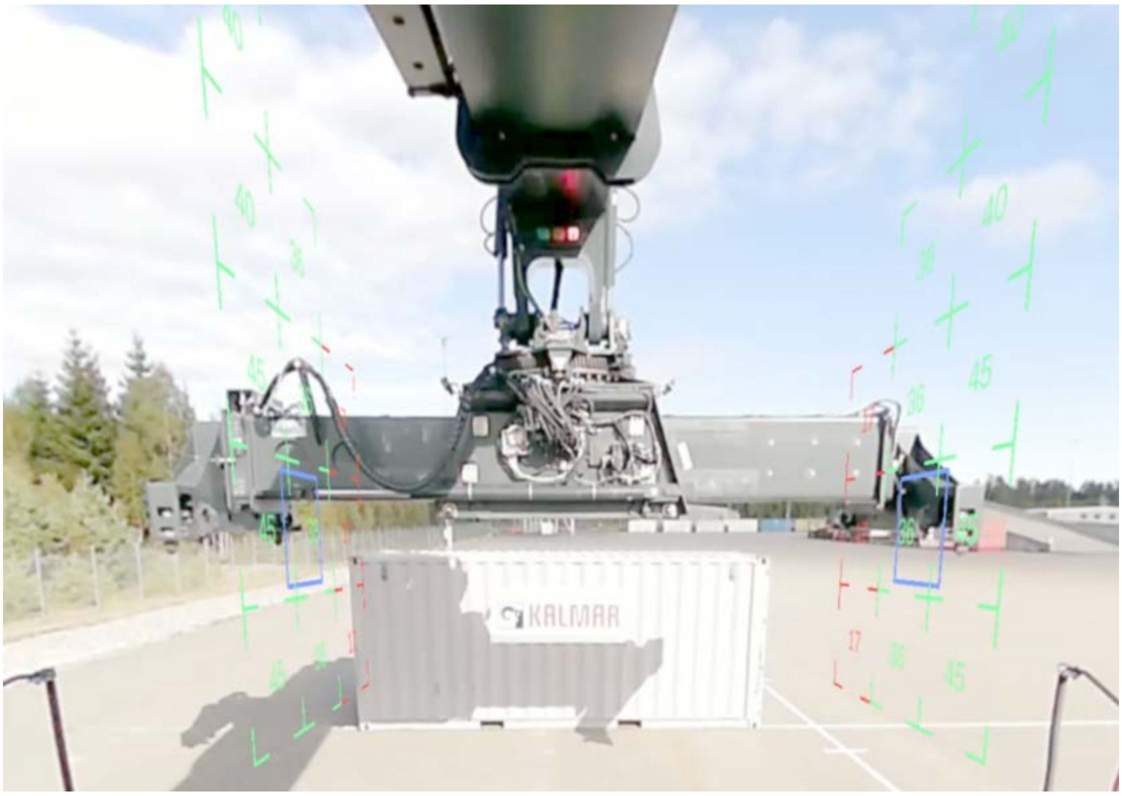



**Figure 28: The load chart UI feature and the blue square**

Making the invisible visible (see Figure 29). When a user is occluded by an object on a specific camera stream, their position is still marked on the UI with a rectangle. This is thanks to the digital twin reconstruction system, which shares information retrieved by one camera (in this case, the Nokia360 camera above) to all the other cameras (i.e., the Cupola360 camera shown below).

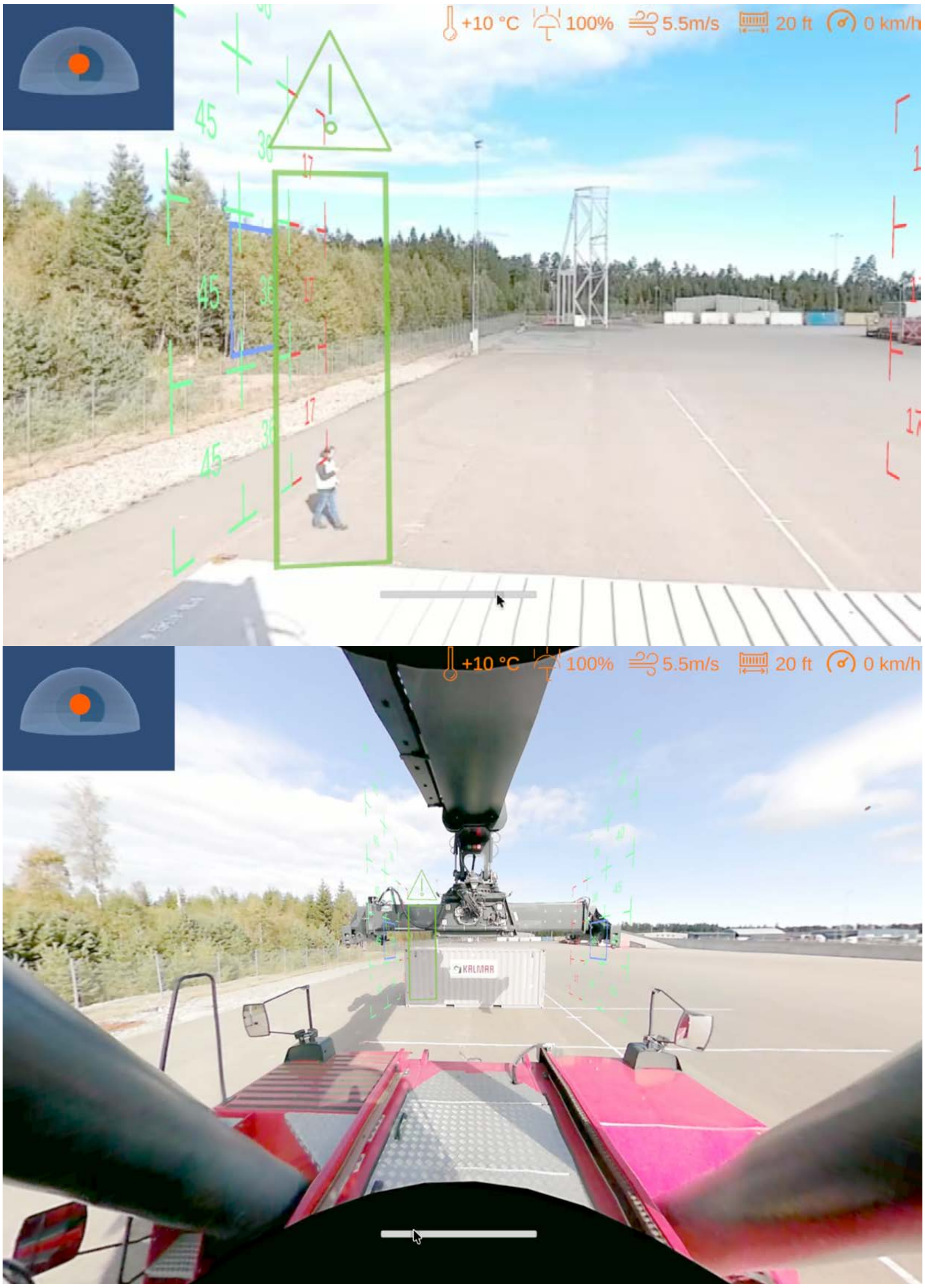



**Figure 29: Invisible user position is still marked on the UI with a rectangle**

Another example of occlusion scenario is shown in Figure 30, this time having the occluded detection on the Nokia360 and the information coming from the Cupola360 camera. The detected people are on the right side of the vehicle. This picture also shows that multiple detections are supported by the system.

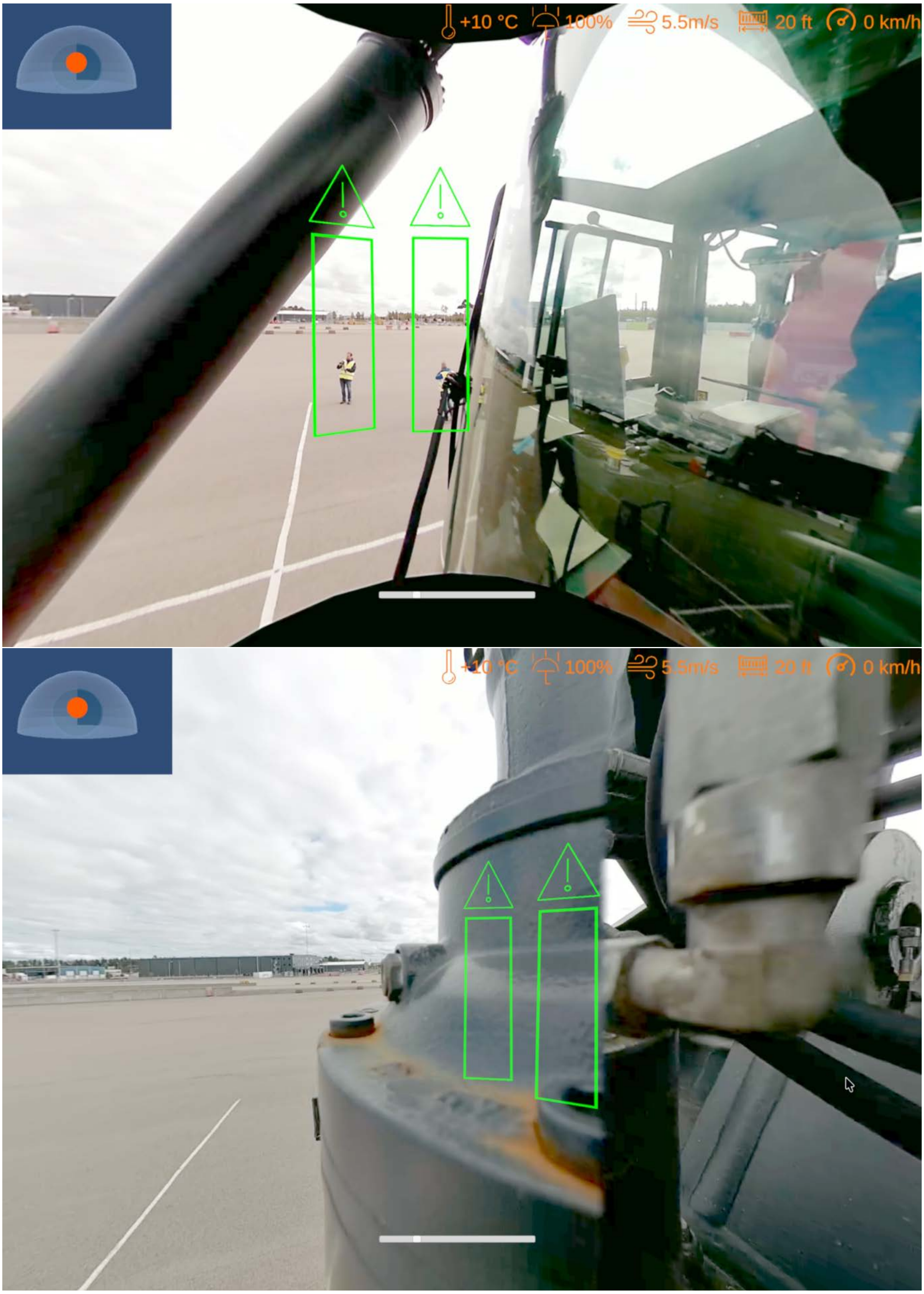



**Figure 30: Example of occlusion scenario**

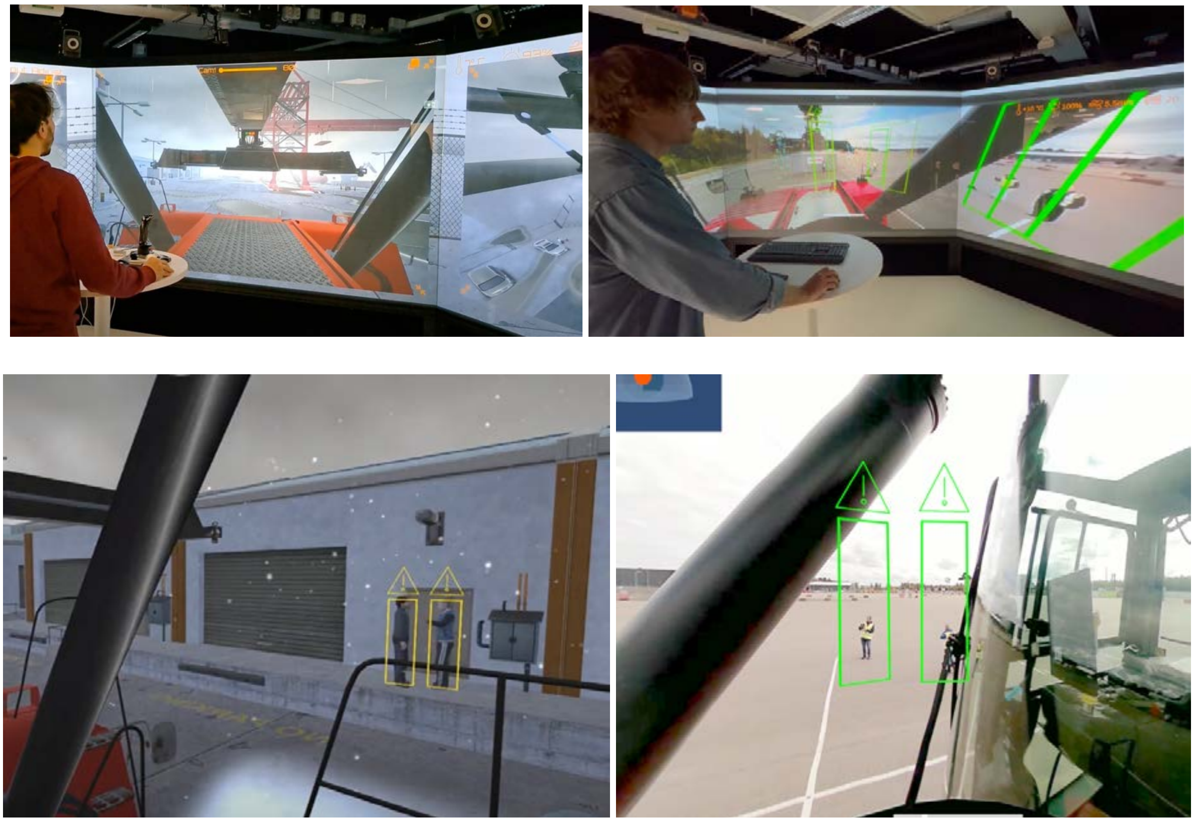
Remote connection to the streams and people tracking system was performed gradually. After everything was confirmed to be working on the local network that we installed on the reach stacker itself, an initial test over cellular data was performed a few meters from the vehicle, by using a second 5G hotspot device which created a mesh with local IP addresses to access resources from the first hotspot device (the one on the reach stacker). Since everything worked as intended, we then moved inside an office cabin close to the test yard facility. There, cellular connection was not optimal, but after trying different positions for the hotspot device, we managed to achieve about 15mbps in download and 5mbps in upload, which were enough for our application to run smoothly. Hand tracking was also tested to work correctly, as expected since panning around the 360 video is performed locally (the application receives the full 360 stream from the RXRM computer on the reach stacker at all times). Finally, the application was even run on our powerwall in Tampere, Finland, thanks to VTT's colleagues at the office. The stream was smooth enough and people tracking worked as intended, with minor tracking errors which are acceptable for the intended use case (those errors could be easily fixed by performing a new calibration to the cameras for the right heights, but time was short because of the returning flights).

**Figure 31: The remote visualization application at the test yard, from an office cabin in Ljungby and from VTT's office in Tampere, Finland**

The application was also tested by two of Kalmar's employees in Ljungby, who are used to operating this machinery on a daily basis, even though for research purposes and not in a logistic facility such as a harbour. The users reported very good feedback regarding usability and UI, even though they admitted that latency was a bit too high for a real use case.

**Figure 32: An employee from Kalmar's Ljungby facility tries the application.**

Overall, this field test demonstrated the feasibility of what was designed and presented in the early-stage simulator. Many of the UI features presented in the simulator were ported as closely as possible to the real application, from the position of the cameras on the reach stacker to the load chart and people tracking UI boxes.



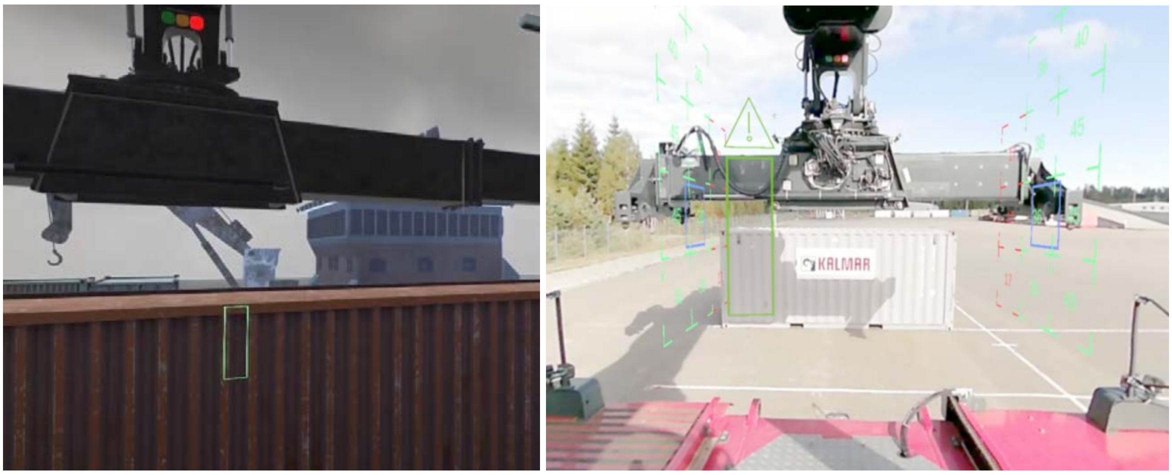



**Figure 33: Some examples of how the UI features were ported from the simulator (left images) to the final application (right images).**

## 3.2 Testing with Demonstrator

Use Case 2 specifically focuses on remotely controlling a reach stacker while handling containers in a harbour. The final user evaluation for the low fidelity prototype demonstrator was organized in VTT’s XR-laboratory in Tampere, Finland, on December 18, 2024. The test was the final pre-implementation test with end users before the actual implementation of the system with the reach stacker.

The VTT development team presented the system to test users, who then performed a container pick-and-place test task with the demonstrator. User feedback was documented during the task. Afterwards, participants completed the SUS questionnaire and took part in a group interview.

***Test users (N=4)***

- 3 reach stacker operators
- Technical manager (supervisor)
- Gender: male

**Evaluation results summary**

The users were generally happy with the system and positively surprised with the development. The learnability of user interface and camera views was experienced as quite good, despite some of the unfamiliar and novel features aimed at remote operation. The users felt they learned to use the system better while progressing with the task. The system was seen as already suitable for pick-and-place containers. According to users, it would have been however interesting to try the driving part, since pick and place was not considered critical from safety perspective. Driving the reach stacker may cause more safety-related issues, thus driving the machine might be a more safety-critical phase in remote operation.

3D perception of the surroundings was mentioned as a challenge still. The top/down camera view was identified as a useful safety feature that is not available with the current reach stacker. This perspective allows visibility behind the container, enhancing situational awareness. The augmented guidance with symbols, lines and changing colors for tracking and placing the container was seen as very helpful and necessary feature in remote operation to support 3D perception. The person detection with visualisation was recognised as an especially important and well-functioning safety feature by the users.

The possibility to organize and customize the user interface (e.g. hide and move camera views and other user interface elements) according to user preferences was seen as a relevant feature. This helps in creating more natural interactions and helps preventing cognitive overload caused by too much visual information.

However, the cabin view (front view from the cabin) should always be visible due to safety reasons. Remote operator should not be able to disable or hide it.

The demonstrator joystick was experienced as difficult to use in the beginning, since the feel of the joystick was different from the real one. It was however quick to learn, according to users. The system also introduced gesture-based control of user interface for changing camera views. All the users found this a feasible option to interact with the system, and two of the operators found this even more convenient than pressing buttons.

According to users, “to feel” and “to see” are more important elements than sounds in reach stacker operation. Visibility and haptic features may play a more important role than sound-based information in remote operation as well. Finally, the users suggested that the system could also be utilised in the training of pick and place tasks.

***SUS questionnaire***
SUS score average for the prototype was **77** (N=4). Based on the average, the system usability was evaluated as acceptable. The SUS scores calculated from individual questionnaires represent the system usability [1]. SUS score starting from 68-70 represents the level of acceptable system usability.

More detailed results have been published in **D3.9**.

## 3.3 Conclusion and lessons learned

The development and deployment of Use Case 2 clearly illustrate how concept design in XR environments can be translated into successful real-world implementation on machinery. The process began with extensive prototyping and testing in XR and laboratory settings, where the system’s core components, including 360-degree video cameras and advanced computer vision algorithms, were integrated and validated (see Figure 33). This preparatory phase allowed the team to anticipate and resolve technical challenges, ensuring that the transition to the actual reach stacker was efficient and required minimal recalibration.

A key innovation in this use case was the integration of 360-degree video with augmented reality overlays and real-time people tracking. The system utilized both Nokia360 and Cupola360 cameras, strategically mounted on the reach stacker to provide comprehensive coverage of the working environment. These cameras streamed immersive 360-degree video to remote operators, enabling them to monitor operations from multiple viewpoints. The video feeds were processed by computer vision software that could detect and track people around the machine, reconstructing their positions on the digital twin of the environment.

Augmented reality played a crucial role in enhancing situational awareness and safety. AR overlays were used to highlight detected people even when they were occluded by objects by sharing information between camera streams and projecting visual cues directly onto the remote operator’s display. This “making the invisible visible” approach ensured that operators could always be aware of personnel in the vicinity, regardless of line-of-sight limitations. Additional AR features, such as load chart visualizations, further supported the operator in complex tasks like container handling with heavy load and risk assessment.

The transition from lab and XR demonstrator testing to real machine deployment was smooth. The hardware and software, once validated virtually, lab, performed reliably in the field, with only minor adjustments needed for environmental differences such as camera mounting height. User feedback confirmed that the AR-based guidance, 360-degree video, and people tracking features significantly improved usability and safety. Operators found the system intuitive to learn and appreciated the ability to customize the interface, while the AR visualizations and top-down camera views provided critical support for both operational efficiency and accident prevention.

In summary, the use of XR in the concept and testing phases enabled a direct and effective implementation on the actual machine. The integration of 360-degree video and real-time people tracking with AR overlays not only made the system easier to set up and use in real-world conditions but also delivered tangible improvements in safety, situational awareness, and user experience. This approach demonstrates the value of immersive technologies in accelerating industrial innovation and ensuring that advanced features are seamlessly transferred from virtual prototypes to operational machinery.

## 4 Use case 3 – Construction

### 4.1 Testing in real life environment

The THEIA$^{XR}$ technologies are implemented in a 18t wheeled hydraulic excavator at TU Dresden. The excavator implements the developed technologies (height indication for finish grading, visualization of detected persons and real-time environment map). The machine and the THEIA$^{XR}$ technologies are fully functional and calibrated to fulfil the desired accuracy. 5 users had the opportunity to test the system in action. Figure 34 shows some impressions of the test site.

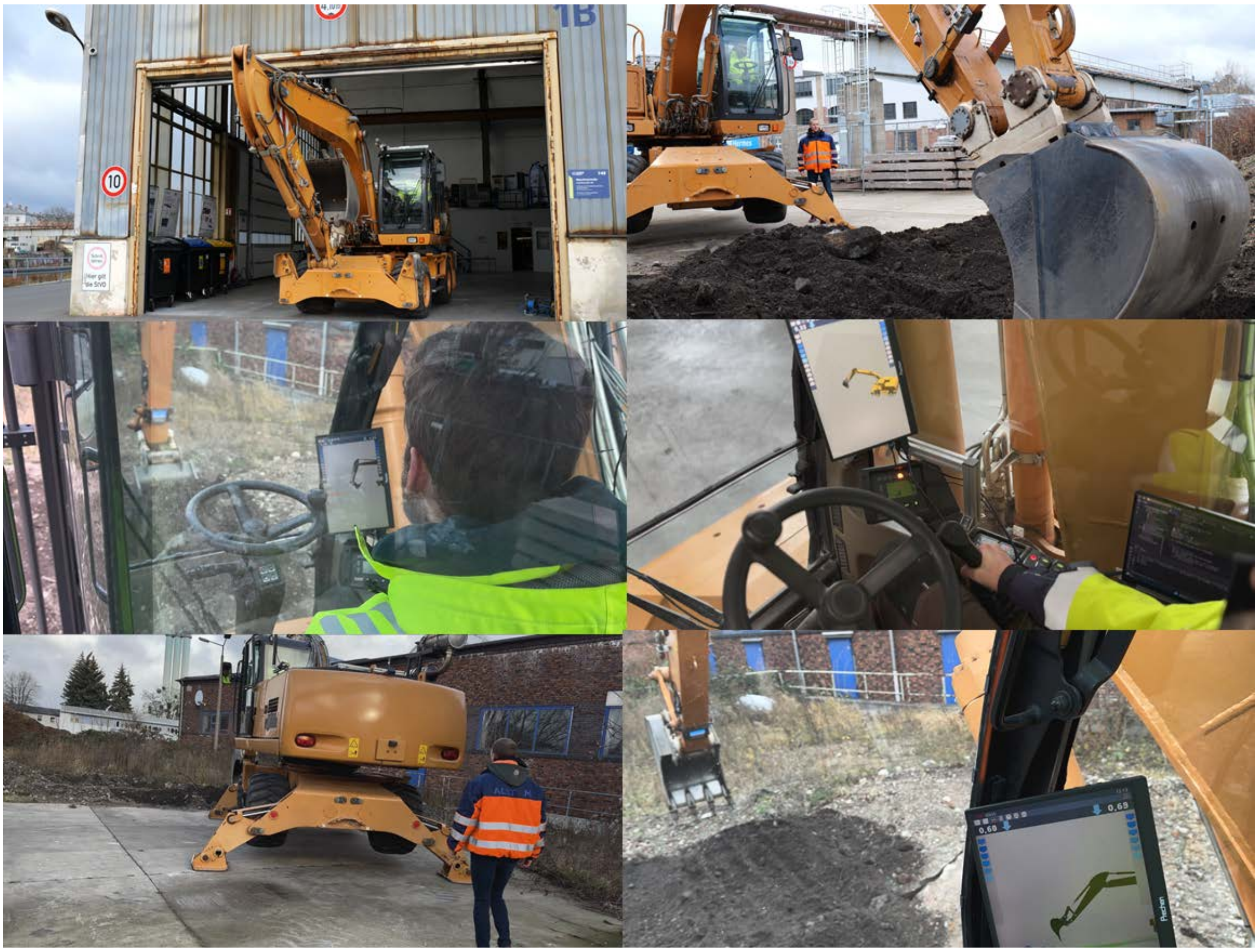


Figure 34: Impressions of the real-life excavator tests

During the first test, the operators familiarized with the excavator by digging randomly on the outdoor test area. After a short familiarization, the users had to dig a pit and move the soil to a defined area by slewing the excavator. The person detection systems and LED-Visualization was activated. Every user understood the system directly and could react appropriately to a person in the danger area. The light was clearly visible and responded quickly, as can be seen in Figure 35.

**Figure 35: The LED-indicator around the front facing window visualizes the direction and distance to persons in the danger zone**

The second task was the levelling of the surface. The users have been introduced to the different modalities that indicate the deviation to the target height. Both, the LED-Matrix-display on the bottom of the arm and the main display (with numbers and colour coded bars) indicate the height deviation. The main display represents the state-of-the-art and every user was familiar with this kind of visualization. The matrix-display was new for all of the users. After an explanation of the visualization, the users have been able to create an even surface with the Matrix-display without the need to tilt the head and look at the main display. Figure 36 shows the LED-matrix display in action. Figure 37 shows, how the bucket can be moved linearly on the target level.

**Figure 36: The LED-matrix display indicates the derivation to the target height**

**Figure 37: Finish grading: The linear movement of the bucket tip is easily controlled by the operator with the help of the height indicators at the bottom of the arm.**

After the levelling task, the users have been presented with the 3D-map of the actual surface, and they should use this visualization to evaluate the quality of their created surface. The visualization both in side view and the isometric display with the colour coding of the deviation was clear and intuitive to all of the users, see Figure 38.


**Figure 38: Sideview of the actual surface in the main display.**

***Test users (N=5)***

- 3 technicians with many years of experience in construction machine operation
- 2 scientific assistants with many years of experience in construction machine operation
- Gender: male

**Evaluation results summary**

The users of the system described it as intuitive, easy to understand, and straightforward to operate, even without extensive prior introduction. They highlighted that the THEIA$^{XR}$ technologies effectively address many of the drawbacks of current systems for person detection and 3D machine control, particularly in terms of responsiveness, situational awareness, and user experience. Several operators mentioned that the spatial visualization and the clear indication of detected persons significantly improve their confidence and safety during machine operation.

However, the major concerns expressed about the system were primarily related to its practical robustness and visibility under challenging environmental conditions. In particular, the visibility of the LED visualizations in bright sunlight was questioned, since the field tests were conducted under cloudy weather conditions. The users were uncertain whether the LED indicators would remain sufficiently visible during outdoor operations in strong daylight. Another critical point concerned the mechanical durability of the installation—especially the LED matrix display mounted on the bottom of the excavator arm. The operators doubted that the display would withstand rough working conditions in the long term, as it might easily be hit by the bucket, the loaded material, or debris from the working environment.

The person detection system itself was considered very useful, reliable, and intuitive, especially when compared to conventional camera-monitor systems that many operators are currently using. The participants emphasized that they appreciate how the system provides immediate, spatially aligned feedback without requiring constant attention to a separate screen. Several users noted that they do not like having to continuously monitor an additional display showing live camera images, as this can be distracting and reduce their overall focus on the machine's operation. In contrast, the Theia$^{XR}$-system integrates this awareness directly into the operator's field of perception, allowing for more natural and efficient interaction.

## 4.2 Testing with Demonstrator

The demonstrator combines a high-fidelity simulation of an excavator digging a pit with the developed THEIA$^{XR}$ components, which serve as a tangible and interactive physical representation of the virtual system, see Figure 39. Through this combination, the interaction with the machine and the immersion in the working process reach a sufficiently high level to effectively showcase the novel technologies within their intended industrial context. The setup includes a main display, a physical and virtual representation of the LED-matrix, and a person detection indication implemented with LED-stripes—all of which are fully functional and presented in real-life scale. This realistic scale and functionality are essential to achieving an adequate sense of presence and authenticity.

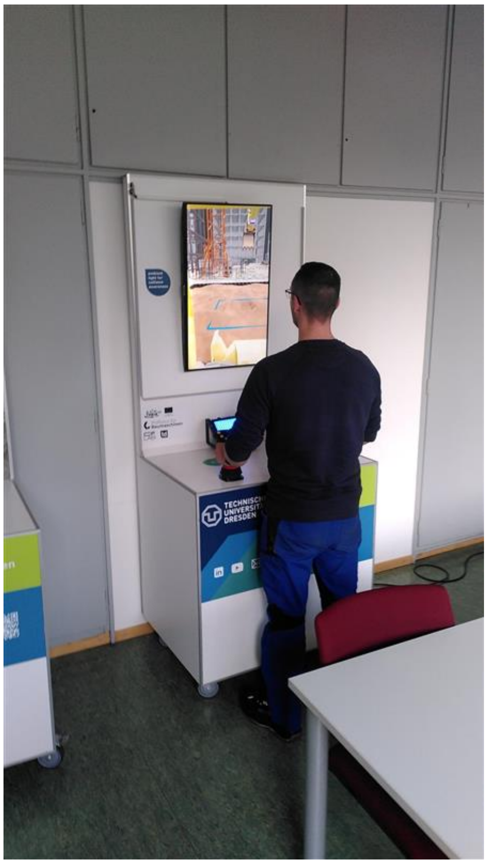


Figure 39: Testing with the demonstrator

In professional environments, operators and engineers are often unfamiliar with purely virtual simulations or design processes that rely on abstract or simplified prototypes. As a result, it can be challenging for them to fully comprehend how new technologies might perform or integrate into their actual working conditions when the demonstrator lacks realism. By providing a system that combines high visual fidelity, physically accurate machine behaviour, and genuine human–machine interface (HMI) components, this demonstrator bridges the gap between conceptual innovation and practical application. The resulting level of realism enables users to intuitively relate to the scenario, better understand the potential benefits of the technology, and provide more meaningful feedback for future development.

The tests with the demonstrator were conducted both in the laboratory of TU Dresden and during the bauma trade fair, involving approximately 30 participants in total. All participants had professional backgrounds in mechanical engineering, the construction industry, or construction machinery operation. Most users quickly understood the concepts and operating principles of the simulation after only a brief introduction. Following the testing sessions, the majority expressed a very positive opinion of the person detection visualization implemented with the LED-stripe. The 3D mapping and the color-coded display of height deviations were perceived as highly innovative and futuristic. However, several operators expressed scepticism regarding its applicability in real machines, citing potential challenges such as vibrations, occlusions, and possible sensor damage that could lead to inaccuracies. In contrast, the LED matrix display was regarded as an easy-to-implement and highly beneficial solution that could realistically be applied in current systems.

## 4.3 Conclusion and lessons learned

The integration of the technologies in both the excavator and the interactive demonstrator clearly demonstrated their value during the development and prototyping phase. These implementations allowed the research team to iteratively test, refine, and validate the concepts under conditions close to real-world operation. Although high-end visualization technologies such as head-up displays or outdoor projection systems could not be employed—mainly due to their limited performance and robustness in our early evaluations—the developed prototypes achieved a level of fidelity that matched the needs and expectations of the operators remarkably well. The focus on practical applicability, rather than purely technological sophistication, ensured that the system remained usable and relevant for everyday construction environments.

The combination of advanced sensing technologies—such as kinematic sensing, 3D scanning, and AI-based object detection—with intuitive, spatially consistent visualizations resulted in a highly positive user experience. Operators particularly appreciated how the system provided context-aware feedback that blended seamlessly with their workflow. This integration not only supported safer operation but also improved efficiency and situational awareness. A crucial element in this success was the close collaboration between developers and end-users throughout the design process. The continuous feedback from operators enabled the development team to align technological capabilities with real-world needs and constraints, ensuring that the final solution was both technically sound and practically meaningful.

A key finding of this work is that the technological component alone—such as an AI-based person detection system—can provide an objective safety benefit, but its true effectiveness and acceptance depend on the way it is presented and integrated into the user interface. If the interface is unintuitive, overly complex, or detached from the operator's natural field of perception, the willingness to adopt the system in daily work will remain low. With the THEIA$^{XR}$ technologies, we were able to overcome this challenge by embedding high-performance sensing and processing components within a user-centric extended reality approach. This approach ensured that the system not only enhances safety but also fosters trust, acceptance, and usability, laying the foundation for future applications of immersive human–machine interaction in construction machinery.

# 5 Conclusions

The project successfully demonstrated the deployment, integration, and validation of advanced operator-assistance technologies across multiple mobile machinery platforms, including snow groomers, reach stackers, and excavators. Initial concepts were iteratively refined through XR-based prototyping, laboratory evaluations, and real-world testing, ensuring robustness, usability, and operator acceptance.

It should be noted that the sample size during testing was limited, and all operators involved were male. Despite significant efforts, recruitment of a female operator was not possible, which represents a constraint for assessing gender-related usability aspects.

Field trials under diverse scenarios confirmed the effectiveness of multimodal guidance systems combining visual projections, haptic feedback, and enhanced operator interfaces. Complementary simulation updates and demonstrator-based evaluations validated immersive visualization and predictive guidance functionalities, highlighting their contribution to operational efficiency and safety.

Key findings include:

- Integrated solutions deliver significantly greater benefits than standalone technologies.
- Operator-centric design and continuous feedback loops are essential for usability and adoption.
- XR-based development accelerates transition from concept to real-world deployment.

The results underline strong potential for industrial adoption and cross-domain application. Future work should focus on extending functionality, improving system robustness under extreme conditions, and leveraging immersive technologies to enhance human–machine interaction in complex operational environments.

# References

[1] Brooke, J. (1996). "SUS: a 'quick and dirty' usability scale," in Usability evaluation in industry. P. W. Jordan, B. Thomas, B.A. Weerdmeester and I. L. McLelland (Eds.) Taylor and Francis Ltd. London, UK.

## ABBREVIATIONS / ACRONYMS

| | |
|---|---|
| **AR** | Augmented Reality |
| **CAN** | Control Area Network |
| **CPU** | Central Processing Unit |
| **ECU** | Electronic Control Units |
| **LED** | Light-Emitting Diode |
| **LIDAR** | Light Detection and Ranging |
| **OEM** | Original Equipment Manufacturer |
| **PC** | Personal Computer |
| **PoE** | Power over Ethernet |
| **RXRM** | Real-time eXtended Reality Multimedia |
| **SUS** | System Usability Scale |
| **UC** | Use-Case |
| **UDP** | User Datagram Protocol |
| **UI** | User Interface |
| **WP** | Work Package |
| **XR** | Extended Reality |