Grant Agreement N°101092861

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

DELIVERABLE 4.4 – INTERACTION CONCEPTS (FIRST VERSION)

This work is part of the THEIA^XR project that received funding from the European Union's Horizon Europe research and innovation program under grant agreement no. 101092861

Funded by the European Union

Document Identification

Project	THEIA^{XR}
Project Full Title	Making the Invisible Visible for Off-Highway Machinery by Conveying Extended Reality Technologies
Project Number	101092861
Starting Date	January 1st, 2023
Duration	3 years
Horizon Europe Programme	Horizon Europe Framework Program (HORIZON)
Topic	HORIZON-CL4-2022-HUMAN-01-14: “eXtended Reality Technologies”
Call for proposal	HORIZON-CL4-2022-HUMAN-01
Type of Action	RIA-Research & Innovation Action
Website	www.theia-xr.eu
Work Package	WP4
WP Leader	TUD
Responsible Partner(s)	HAP
File Name	D 4.4 – Interaction concepts (first version)
Contractual delivery date	29.2.2024
Actual delivery date	27.3.2024
Version	1
Status	Final
Dissemination level	Public
Author(s)	Thomas Howard (HAP), Sebastian Lorenz (TUD), Volker Waurich (TUD), Manuel Kulzer (HdM), Tanya Brodbeck (HdM), Laura Makinen (KAL), Pekka Yli-Paunu (KAL), Martijn Rooker (TTC), Kaj Helin (VTT), Andrea Alesani (VTT), Clemens Arth (TUG), Thomas Kernbauer (TUG), Daniel Röck (PRIN)
Contact details of the coordinator	Martijn Rooker, martijn.rooker@tttech.com
Internal Reviewer	Sebastian Lorenz, Volker Waurich, [TUD] Clemens Arth, [TUG]

Disclaimer

Funded by the European Union	Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Commission. Neither the European Union nor the granting authority can be held responsible for them.

Executive summary

This deliverable presents the first set of results from task T4.4 "*Multimodal interaction concepts and resulting requirements for XR-Technology and UI*". The goal of this task is to develop a general interaction model, wherein all the envisioned control and feedback functions relevant to each of the THEIA^{XR} use-cases can be described. Using this, we break down the interaction scenarios developed in task T3.2 into component control and feedback tasks, to specify concrete implementations of these functions to be tested in the project. By iteratively refining these implementations based on input from the co-design process as well as insights gleaned during the implementation process, we will converge towards a set of functional and relevant novel interactions to be showcased through immersive playable demonstrations. The present document aims to provide a first draft of a specification for these demonstrations.

Table of Contents

List of Figures

List of Tables

1 Introduction

Deliverable D4.4 aims to produce a general model of interactions, along with a set of immersive playable demonstrations showcasing novel control and feedback functions developed for each of the use-cases considered in THEIA^{XR}.

This version of the deliverable presents the interaction model, followed by current progress in ideating and designing specific control and feedback functions for each use-case. It also presents an initial specification for each of the three demos that could be implemented in relation to the use cases. The final version of the deliverable will refine the proposed ideas based on feedback from the co-design process from work package WP3 (in particular task T3.2). Additional feedback on technical feasibility and performances of input, sensor and display hardware from work packages WP4, WP5 and WP6 will be used to refine the concepts proposed here and to eliminate options that are not realizable. We will thus converge towards final specifications for the demonstrator scenarios which will be implemented as the D4.4 deliverable. Insights from the UI design taking place in this deliverable will feed into deliverable D4.5.

Work in task T3.2 and deliverable D3.2 respectively is still ongoing. A first version of the UC1 vision scenarios has already been validated in co-design workshops with snow groomer operators, but the validations of UC2 and UC3 vision scenarios is still pending due to time-limited availability of operators (UC3 co-design workshops will take place in March 2024, UC2 workshops have yet to be arranged in accordance with KAL customers). Therefore, the present specification is based on the initial vision scenarios created in T3.2 based on user research (T3.1) and will likely be subject to change as we collect more feedback from operators about the feasibility and desirability of the proposed features. Deviations of the final demonstrations from the plan laid out in this document will therefore be discussed in the final version of the deliverable, once all information from WP3 has been collected.

Section 2 presents a brief summary of theoretical work on interaction modeling used as a framework for ideation of control and feedback functions. Each of the three use-cases of the THEIA^{XR} project is then dealt with in Sections 3, 4, and 5 respectively. For each use-case, we begin by presenting an analysis conducted on the scenarios produced in deliverable D3.2 which serve as a basis for ideating control and feedback functions (see Figure 1). This analysis produced a set of component tasks which are further decomposed into individual control and feedback functions. For each of these functions, we discuss the state-of-the-art, followed by visionary concepts that could be implemented in the THEIA^{XR} project. This aims to ensure that all control and feedback functions which will ultimately need to be implemented in the demonstrators are fully described.

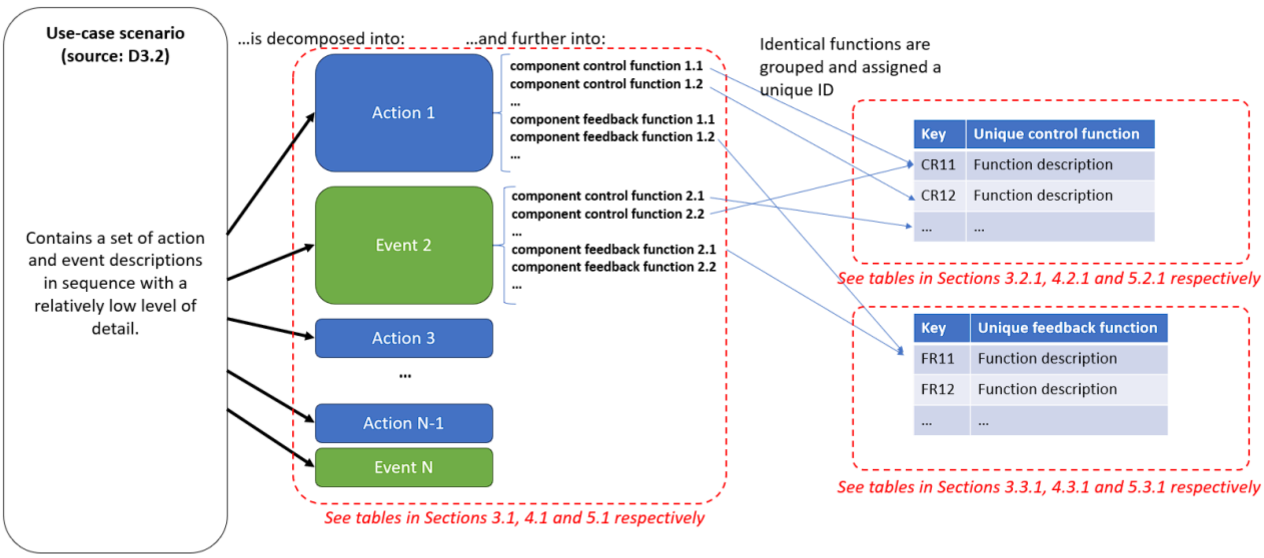

Figure 1: Methodology for establishing the list of control and feedback functions of interest

2 Interaction model

Based on the sender-receiver model in communication theory [1] we used interaction modelling to describe how the technical system responds to identified information requirements in various scenarios of machine operation. In this research, the technical system consists of the machine, including its structure, sensors, controllers, and actuators, and the human-machine interface (HMI), that uses data on system states from various internal and external sources to provide information (sender) to the operator (receiver). As HMIs are sensitive to distinct ways of interaction, operators also can send information to the receiving HMI. However, in this first phase of interaction concepts we focused on the first relation, by defining how information can be presented to the operator. Based on the developed modality framework, reported in deliverable D4.3., this utilized three levels of description. Level one depicts what information is presented (e.g., raw sensor data, or (more likely) pre-processed data from various sources). Level two defines how the information is presented which covers several subjects. This level clarifies, (1) where the information is presented (device, location in the cabin, location in the virtual user interface), (2) which modality is used (e.g., visual, acoustic, haptic modality, as well as the presentation technique, e.g., visual graphic, animation, vibration pattern), and (3) details the design of the information presentation. This design explores and defines all the associated designable degrees of freedom. Eventually level 3 defines how this information presentation behaves in relation to changes in system states or operator input.

The process for the functional analysis conducted below in Sections 3, 4 and 5 with the aim of designing the envisioned control and feedback functions is the following (see also Figure 2): Any event in a vision scenario (described in deliverable D3.2) requires either the implementation of a control function (i.e., the operator acts on a user interface (UI) element to trigger and control an action executed by the vehicle, tool or UI), the implementation of a feedback function (i.e., the UI provides feedback elaborated by the vehicle's internal software on the basis of acquired sensor values and internal processing), or both.

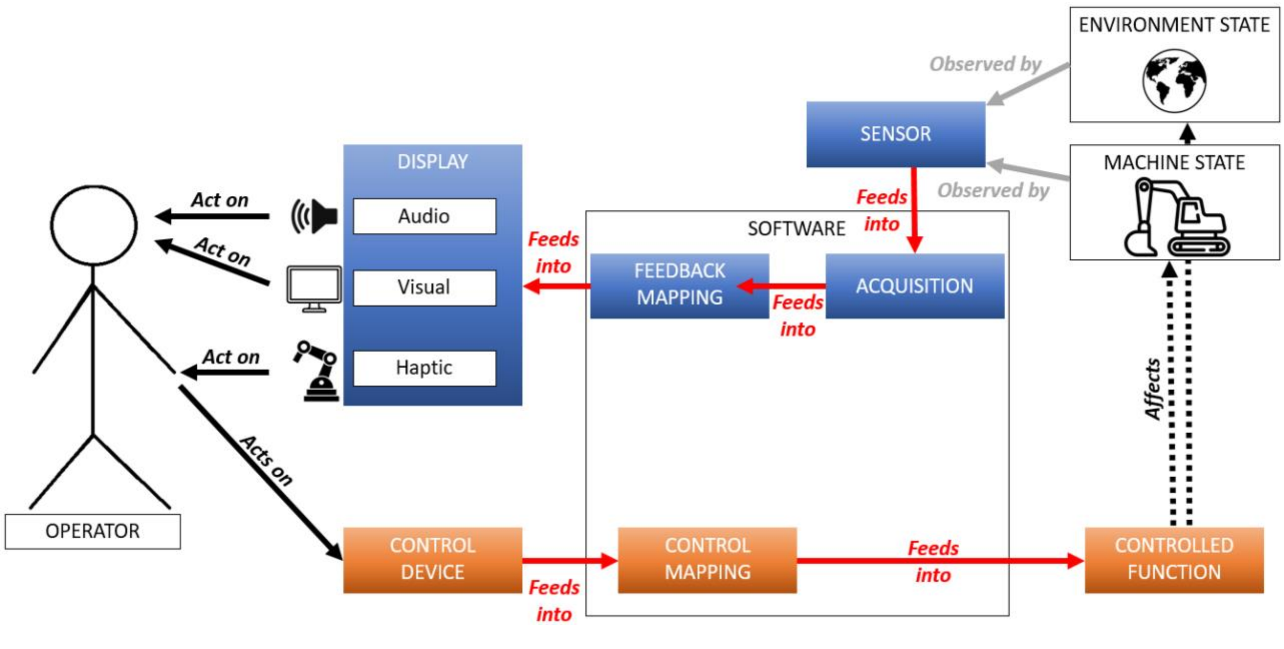

Figure 2: Interaction model used to define component control and feedback functions

A control function can be fully described by the UI elements that are used to execute it, the output values of interaction with these UI elements, the mapping of these output values to tool setpoints, and the tool executing the action (orange pathway in Figure 2). A feedback function can be fully described by the sensors or algorithms producing the input data, the output values of these sensors or algorithms, the mapping of these output values to display element output values, and the display element providing the feedback (blue pathway in Figure 2).

The analysis of the vision scenarios presented in Sections 3.1, 4.1 and 5.1 respectively for UC1, UC2 and UC3 yields a set of unique control and feedback functions for each use-case. For UC1, these functions are summarized in Table 11 and Table 12 in the appendix Sections 7.1 and 7.2. Similarly, for UC2, summary tables (Table 13 and Table 14) are provided in the appendix Sections 7.3 and 7.4. The summary tables for UC3 (Table 15 and Table 16) are provided in the appendix Sections 7.5 and 7.6). Each function is identified using a unique function key, following the naming convention “C” for “control” or “F” for “feedback”, “R” or “V” for the “*realistic*” or “*visionary*” scenario respectively, followed by the use-case number and the function number. This convention is used in the rest of the document for easy and concise reference when discussing implementations. The discussion of control function implementations relevant to the design of the demonstrators is presented in Sections 3.2, 4.2 and 5.2 respectively for UC1, UC2 and UC3. Similarly, the discussion of feedback function implementations relevant to the design of the demonstrators is presented in Sections 3.3, 4.3 and 5.3.

3 Use-case 1: Snowgroomer

3.1 Scenario analysis

Task T3.2 provided a set of two scenarios for the snow grooming use-case: a "*realistic*" scenario focused on control and feedback functions implementable in-vehicle in the short term, and a "*visionary*" scenario focused on a more long-term perspective of a potentially teleoperated vehicle. For each of these drafts, we proceeded to decompose the scenario events into implied component control and feedback actions. This formed the basis for our collective ideation of control and feedback functions described in Sections 3.2.2 and 3.3.2 The result of this analysis is presented in Table 1 and Table 2 below.

Scenario section	Component task
Marco carries out a brief safety inspection of the machine and starts the engine.	**Control:** Operator starts the engine.
The color coding of various light bars inside the snow groomer allows him to see the general condition of the vehicle and the status of the various systems at a glance	**Control:** Operator activates vehicle diagnostics. **Feedback:** Inform operator of safe machine state. **Feedback:** Inform operator about successful engine start.
Marco had feared yellow, which would have meant that maintenance was due soon. Red would have meant that the vehicle's condition is not suitable for the intended use and Marco would have had to choose another vehicle.	**Feedback:** **Feedback:** Inform operator of pending maintenance. **Feedback:** Inform operator of unsuitable state of vehicle for intended use.
Outside the vehicle, Marco can see the assistance system's guidelines on the ground to obtain information such as the width of the vehicle and its alignment. This allows him to better estimate the dimensions and makes it easier for him to steer the vehicle out of the garage.	**Control:** Operator activates navigation assistance system. **Feedback:** Inform operator about vehicle width **Feedback:** Inform operator about vehicle alignment
As Marco drives into the area where he has to carry out his work, he can intuitively recognize when he has reached his destination by the bright laser projections on the ground in front of the vehicle changing colors.	**Control:** Operator drives vehicle. **Feedback:** Inform operator about location of work area. **Feedback:** Inform operator that work area has been reached.
As Marco adjusts the blade and tiller, the interior and display ambient lights turn red because he is outside the optimal parameters suggested by the system.	**Control:** Operator adjusts blade settings. **Feedback:** Inform operator about current blade settings and state. **Feedback:** Inform operator about discrepancies between current blade settings and optimal calculated blade settings. **Control:** Operator adjusts tiller settings. **Feedback:** Inform operator about current tiller settings and state **Feedback:** Inform operator about discrepancies between current tiller settings and optimal calculated tiller settings.
While adjusting the blade and tiller, Marco occasionally presses a button activating haptic guidance, generating a gentle pull of the joystick towards the orientation originally calculated so as to achieve optimal placement of the tool.	**Control:** Operator triggers the haptic guidance for blade or tiller positioning. **Feedback:** Inform operator about discrepancies between current tiller settings and optimal calculated tiller settings.

In the lower part of the track, he receives direct feedback that a lower speed is recommended – especially since fresh, light, and soft snow has fallen in the meantime.	**Feedback:** Inform operator about recommended speed.
In addition, he is advised to set a lower pressure for the tiller.	**Feedback:** Inform operator about recommended tiller pressure.
Luckily, Marco has activated the assistance system, which now signals that the blade is set too low by a red light inside the vehicle.	**Feedback:** Inform operator about incorrect blade settings
Marco also receives haptic feedback from his joysticks to warn him not to dig too deep into the snow	**Feedback:** Inform operator about excess snow digging depth
However, he took away a bit too much snow, so now he needs to reverse and repair the surface with snow from a different part of the slope.	**Feedback:** Inform operator about damage to slope. **Control:** Operator reverses vehicle to a desired position. **Feedback:** Inform operator about available excess snow to be used for repairs. **Control:** Operator collects snow from different part of slope. **Control:** Operator transports snow to target location. **Control:** Operator repairs damaged surface. **Feedback:** Inform operator about successful repair of damaged slope.
Marco activates the "poor visibility support" of the assistance system.	**Control:** Operator activates "poor visibility support" system. **Feedback:** Inform operator about successful activation of the "poor visibility support" system.
Bright blue laser lines indicating the vehicle's dimensions and a white grid are now projected on the ground in front of the vehicle. The grid illuminates the snow surface in front of the vehicle and helps detect bumps, obstacles and the general condition of the ground.	**Feedback:** Inform operator about vehicle dimensions relative to slope in poor visibility conditions. **Feedback:** Inform operator about bumps and obstacles in poor visibility conditions. **Feedback:** Inform operator about general condition of the ground.
One line represents the horizon, which would otherwise be barely perceptible.	**Feedback:** Inform operator about the horizon location and orientation in poor visibility conditions.
As he glances at the onboard snow measurement system, he can also see the position and alignment of his vehicle on the slope in a real time 3D view.	**Control:** Operator activates 3D visualization of vehicle position on slope. **Feedback:** Provide a 3D visualization of vehicle and slope to operator.
As Marco approaches a stationary snow cannon, the projected guide lines outside the vehicle change color from blue to orange and then to red. The ambient lighting inside the vehicle also changes color in this way, warning him before getting too close.	**Feedback:** Inform operator about the presence of obstacles in the vicinity. **Feedback:** Inform operator about the nature of obstacles in the vicinity. **Feedback:** Inform operator about the distance and/or direction to obstacles in the vicinity.
The snowfall has subsided and Marco approaches a steep part of the slope where he needs to use the winch.	**Feedback:** Warn operator that winch is required.

He slowly drives towards the upper edge of the slope, gets out of the vehicle and attaches the winch cable to the anchor point. Then he re-enters the vehicle and slowly descends the slope. While using the winch, ...	**Feedback:** Inform operator about successful winch anchoring. **Control:** Operator drives winch winding. **Feedback:** Inform operator about winch cable tension. Inform operator about winch cable direction or path. Inform operator about a hazard in winch operating area.
He looks into the direction where the red area had appeared and in the light cone of the smart spotlight, he sees a lone skier descending the slope next to him …	**Control:** Operator activates smart spotlight. **Feedback:** Inform operator about the direction towards or location of a hazard in the vicinity. **Control:** Operator directs smart spotlight direction.
Marco sighs and waits for him to pass while a red flashing ring is being projected around the vehicle, indicating the danger zone for skiers.	**Control:** Operator activates environment warning system. **Feedback:** Inform operator of successful activation of the environment warning system. **Feedback:** Inform persons in vicinity of the danger zone around the vehicle.
Marco's first shift is completed, …	**Feedback:** Inform operator about progress on or completion of planned work.

Table 1: Component tasks for UC1 "realistic" scenario

There is significant overlap in the tasks to be performed and information fed back between the "*realistic*" and the "*visionary*" scenario. Therefore, we only highlight the differences in Table 2 below.

Scenario section	Component task
After quickly discussing the first shift with his colleagues in the hallway, he heads to his desk, sits down in his comfortable office chair, puts on the XR helmet and starts his shift. After selecting and connecting to his vehicle, the inside of the vehicle garage appears in front of him and he now sees "through the snow groomer's eyes". Marco must maneuver between the garage door and two other vehicles. He therefore switches back and forth between the left and right cameras and a bird's eye view, allowing him to steer the vehicle precisely without blind spots...	**Control:** Operator puts on the XR helmet **Control:** Operator selects and connects to his vehicle **Feedback:** Provide operator with a view "through the snowgroomer's eyes" **Control:** Operator selects suitable camera view
As Marco drives up the slope, the system recognizes his progress along the route and informs him when he has reached the section to be worked on. He can see the ideal route highlighted on top of the actual terrain...	**Feedback:** Inform operator about ideal route to work area. **Feedback:** Inform operator about progress along a route.
As Marco is supported by the assistance system, the route being worked on is continuously monitored by the reversing camera.	**Feedback:** Inform operator about insufficient slope quality. **Feedback:** Provide operator with rear view towards finished slope

Table 2: UC1 "visionary" scenario additional functions

3.2 Availability of control functions (input)

The analysis of the vision scenarios presented in Section 3.1 above yields the list of individual control functions summarized in Table 11 in the appendix Section 7.1. Below, we discuss the functions already implemented in part or in full in the state of the art, followed by a description of all proposed novel implementations.

3.2.1 State of the art

In this section, we briefly cover how the control functions considered that can currently be executed in snowgroomers are implemented. This will serve as a baseline for quantifying proposed improvements in our envisioned interactions described in Section 3.2.2 below. It will also serve as a specification for implementation of unchanged control functions that need to be included within the playable demonstrations.

The operator starts the vehicle using a push-button or key-switch (CR11 and) drives the vehicle using the right-hand pair of track controls and pedal (CR14).

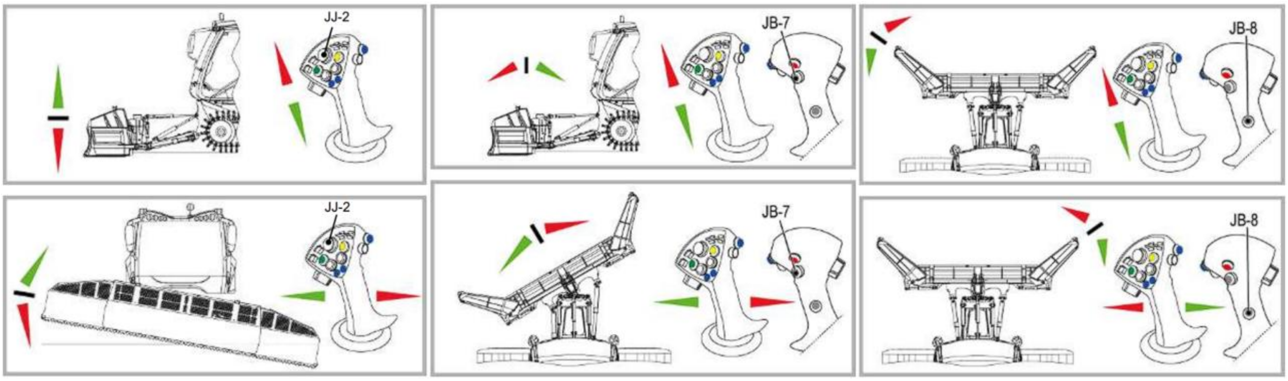

Figure 3: Existing mapping between joystick controls and blade motions

Currently, blade pose is controlled by using the main joystick's two axes of rotation combined with one of three push-buttons, which map joystick rotations either to blade height and roll, blade tilt and pan, or left or right blade opening and closing (see Figure 3). Joystick angles linearly map to blade element angular velocity in each case.

Figure 4: Joystick-in-joystick feature

The multiple functions of the tiller (see Figure 5) are controlled using combinations of pushbuttons, the joystick rotations, as well as potentiometers and the joystick-in-joystick feature (see Figure 4) on the primary joystick.

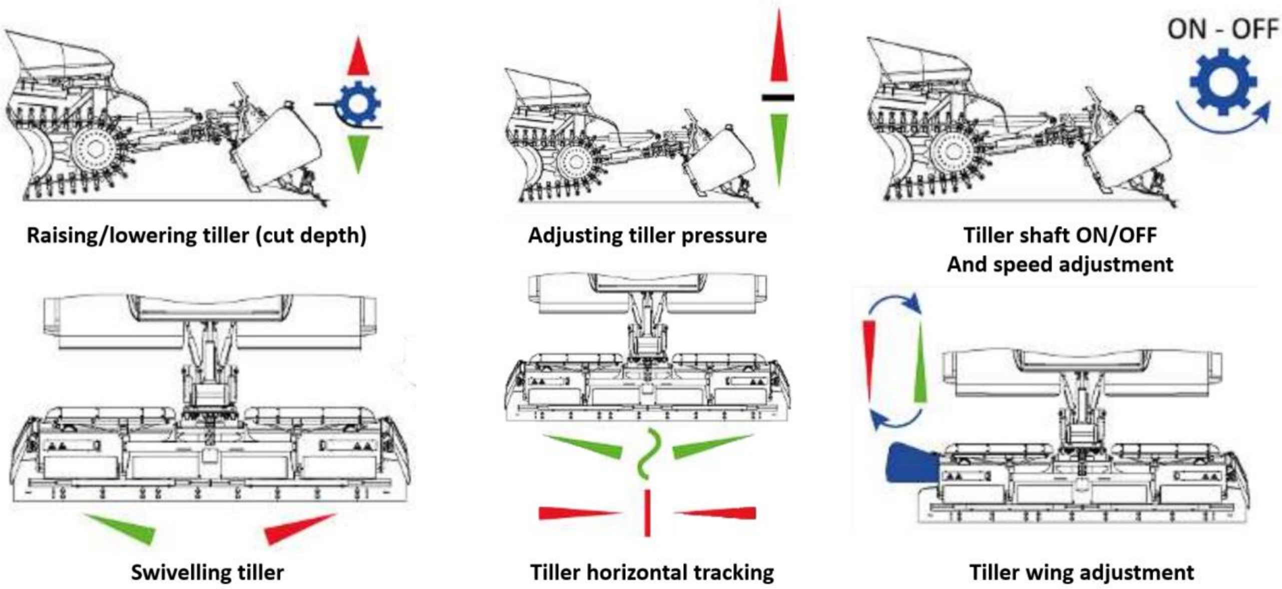

Figure 5: Controlled tiller functions

Currently, collecting and transporting snow to build or repair surfaces (CR19, CR110, CR111) involve a combination of driving the vehicle to a location with excess snow (see CR14 above) as well as adjusting the blade and tiller settings (see CR15 and CR16 above) to separate a certain amount of snow from the surface and push it to the target location.

In vehicles equipped with 3D visualization systems (see Figure 11 below), these are activated using the buttons on the relevant displays (CR113).

Operators start or stop the winch and then continuously adjust the pull exerted on the winch cable during operation using controls on the control unit and primary joystick (CR114). Furthermore, depending on the vehicle, operators may be able to adjust the rotation behavior of the winch tower to better control the cable path. When winching it is possible to have 1.2km of winch cable between the vehicle and the anchor point sitting on the top of the grooming area. Therefore, additionally to the winch force setting, the operator has to make sure that the cable doesn't hit or get tangled in objects surrounding the operational area. Furthermore, the operator has to minimize the damage caused by dragging the cable over the already groomed surface. This makes path planning experience critical during winch operation.

Although there is no "smart spotlight" yet as state-of-the-art on snowgroomers, vehicles are equipped with a manually controlled spotlight which can be switched on and off and directed using a dedicated handle in the cabin roof (CR115, CR116).

The control function CV11 from the visionary scenario is rather trivial in terms of execution, as it implies only standard use of an XR headset and will thus not be discussed further.

3.2.2 Envisioned control functions

This section describes the innovations beyond the state of the art that are in the process of being prototyped or will be prototyped by the THEIA^{XR} partners, grouped by the control function that is to be achieved.

3.2.2.1 Operator activates vehicle diagnostics. (CR12)

By using the intuitive graphical user interface dispatched on the display mounted in the vehicle cabin, the human operator can activate different functionalities or information of the machine. In the case of vehicle diagnostics, the important information must be displayed directly in an intuitive and direct manner, informing the operator about possible situations. The aim is to remove the need for pressing too often on the display and display the information directly to the operator, so that he isn't distracted too long from the task at hand and can focus most of the time on the work to be performed.

Implementing this control function will require the demonstrator simulations to interface with the main physical touchscreen display, which is discussed in deliverable D5.5 (see also Section 3.4.2). The result of this function activation is discussed below in 3.3.2.

3.2.2.2 Operator activates navigation assistance system. (CR13)

Assuming that a navigation assistance system based on GNSS or GPS data is available, activating it is probably best performed by interacting with the GUI of the in-vehicle touchscreen display.

3.2.2.3 Operator adjusts blade settings (CR15)

By using the novel haptic input device developed in the scope of deliverable D5.5 (see also Section 3.4.2), it will be possible to explore novel input mappings for the functions controlled with the main joystick. In the case of the blade, we expect to be able to test a simplification of the main blade control by removing the need for push-button selection of the controlled axes and using a 4DoF input control scheme to control blade height, pan, tilt and roll all at once.

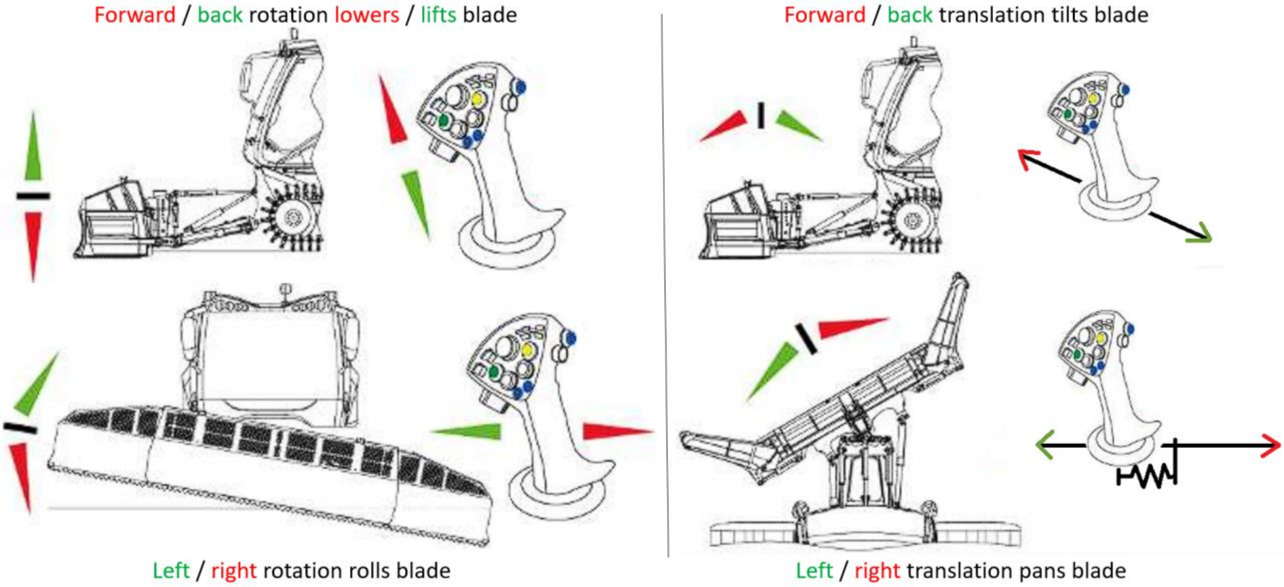

Figure 6: Proposed novel mapping of 4DoF joystick input motions to blade motions

For example, we wish to test mapping blade tilt to a translational motion along the joystick X axis and blade pan to a translational motion along the joystick Y axis (see Figure 6). A variation on this would be to map blade pan to a semi-circular arc motion around an axis parallel to the joystick Z axis (see Figure 7). This may present the advantage of providing a more ergonomic manipulation as the operator's elbow could remain more or less fixed in position on the armrest.

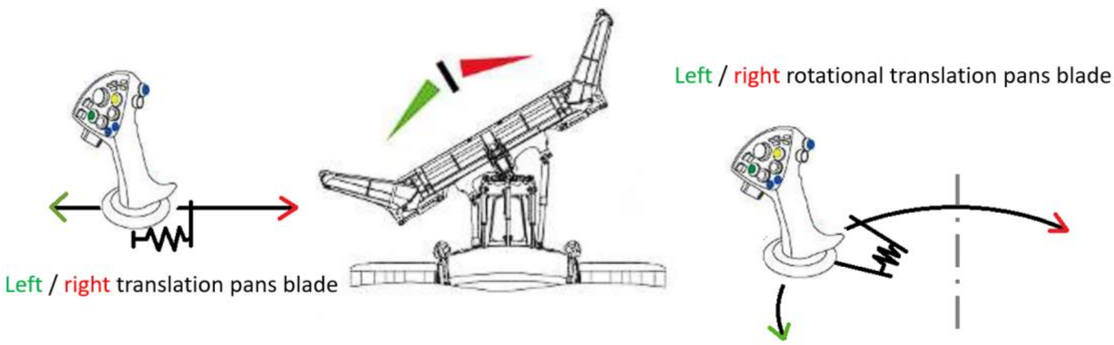

Figure 7: Possible variation for the left/right translation control

3.2.2.4 Operator adjusts tiller settings (CR16)

We could replace the need for buttons which select the left and right tiller wings in order to map the joystick forward and back rotation to their raising or lowering. Translationally shifting the joystick to the left or right could allow for intuitive selection of a blade wing, while forward/back rotation could still be used to raise and lower it (see Figure 8).

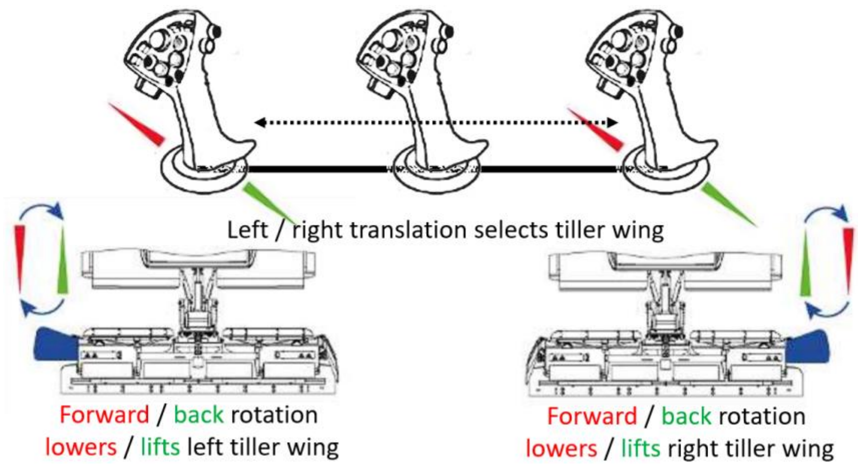

Figure 8: Proposed translational joystick motion for selecting tiller wings

Gradually raising and lowering the tiller could also be implemented by translational motions along the joystick X axis (similar to those shown in Figure 6 top right).

3.2.2.5 Operator triggers the haptic guidance for blade or tiller positioning. (CR17)

The envisioned haptic guidance for assisting blade and tiller positions (see discussion of feedback functions FR110, FR112, FR114, FR115 and FR122 below in Section 3.3.2) should not be active at all times as this will likely be more disturbing than helpful for operators. Instead, two free push-buttons which do not map to any blade or tiller control functions should be used to toggle between blade positioning assistance on/off and tiller settings assistance on/off. A toggle button is preferable to a button requiring constant pressing since the operators need to press other buttons simultaneously, especially when operating the tiller.

3.2.2.6 Operator activates "poor visibility support" system (CR112)

Similar to the vehicle diagnostics above, the activation of the "poor visibility support" system, can be performed by pressing a button on the Graphical User interface within the cabin (informing the operator in an intuitive way that the system has been activated. As this function likely only requires occasional activation and disabling, mapping a button on the joystick to toggle between both states is probably not helpful. This control function will require the demonstrator simulations to interface with the main physical touchscreen display, which is discussed in Section 3.4.2.

3.2.2.7 Operator activates 3D visualization of vehicle position on slope. (CR113)

The activation of the "3D Visualization" system can be performed by pressing a button on the Graphical User interface within the cabin (informing the operator in an intuitive way that the visualization has been activated). As the activated feedback is somewhat state-of-the-art, the result of this function is discussed in Section 3.3.1.

3.2.2.8 Operator activates smart spotlight. (CR115)

Similar to vehicle diagnostics, the activation of the smart spotlight can be performed by pressing a button on the Graphical User interface within the cabin (informing the operator in an intuitive way that the spotlight has been activated).

Alternatively, since the smart spotlight may require frequent activation, it may be sensible to map a toggle button on the primary joystick to its activation/deactivation. In the case where the smart spotlight would also be directed by the joystick, a constant press on this button could map joystick motions to smart spotlight motions, while release would return the joystick to whatever other function it can control. In this case it may be sensible to decouple smart spotlight activation/deactivation from its control by e.g., mapping a double-click on the smart spotlight button to its activation/deactivation, and a constant press to its direction control (see also discussion of control function CR115 below).

The beam of the smart spotlight provides implicit feedback on the success of this control function. Therefore, no additional feedback needs to be provided to the operator following this control action.

3.2.2.9 Operator directs smart spotlight direction. (CR116)

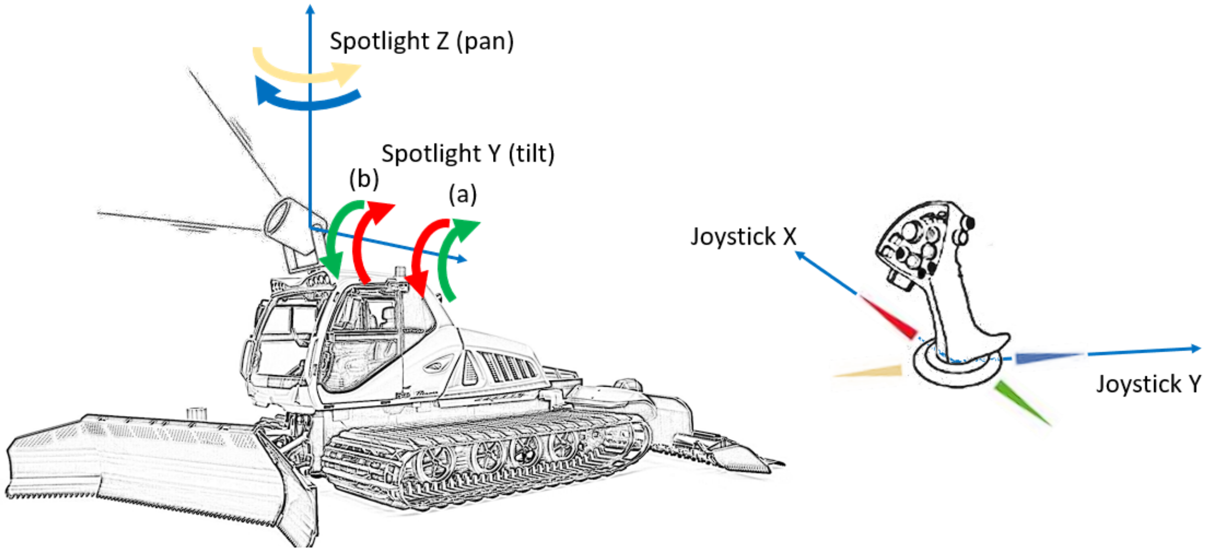

Figure 9: Proposed mappings of joystick motions to spotlight motions

The smart spotlight direction is defined by two rotation angles around the center of the spotlight. It can therefore be mapped to the two rotational axes of the joystick in a straightforward manner. Two options come to mind in terms of mapping (see also Figure 9):

(a) The joystick rotation around X (side to side motion) maps to angular velocity around the spotlight pan axis and the joystick rotation around Y (front to back motion) maps to angular velocity around the tilt axis.

(b) Same as above except the tilt axis rotation is inverted. The effect of this would be to control the spotlight in a similar manner as if it were a pointer towards the field of view of the operator. Tilting the joystick forward would cause the spotlight to rotate up, thus projecting the beam further out, i.e. into the “top” of the operator’s field of view and vice versa.

Of course, since useful spotlight range of motion is limited, it may also be sensible to consider mapping angular position of the joystick to angular positions of the spotlight following either of the schemes discussed above. Whether this remains intuitive in the context of other vehicle functions based mostly on position to velocity mappings remains to be tested.

3.2.2.10 Operator activates environment warning system. (CR117)

Similar to the vehicle diagnostics, the “environment warning” system can be activated by pressing a button on the Graphical User interface within the cabin (informing the operator in an intuitive way that the system has been activated). Feedback to the operator and to persons in the vicinity resulting from this is discussed in Sections

The environment warning system is a function which should be readily available to the operator at any time. To ensure quick access, it may be sensible to provide a switch or push-button on the primary joystick that activates or deactivates the function. Of course, the added clutter in terms of joystick controls should also be carefully considered.

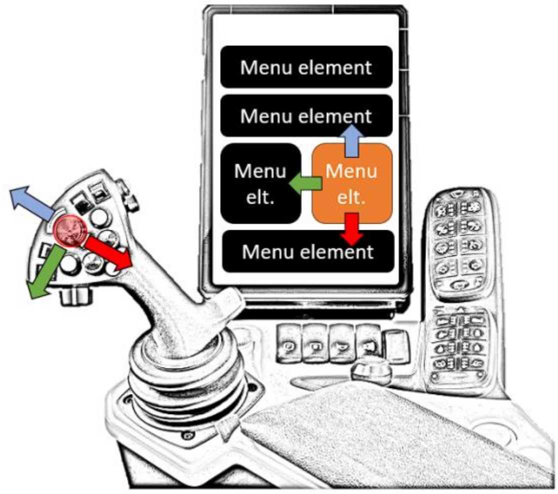

Figure 10: Proposed joystick-in-joystick UI navigation feature

3.2.2.11 Operator selects/connects to his vehicle (CV12)

To minimize the number of control elements in a teleoperation scenario, we could envision using the primary joystick (or joystick-in-joystick) to navigate a menu of available vehicles, either through joystick rotational motions around X and Y, or through joystick translational motions around X and Y. A pair of pushbuttons on the joystick could be used to select or cancel selection (see Figure 10).

However, if a touch-panel is available, it will probably be more ergonomic to use that for interacting with menus.

3.2.2.12 Operator selects suitable camera view (CV13)

Similar to the task of selecting and connecting to a vehicle, the joystick-in-joystick feature of the primary input device could be used to seamlessly cycle through available camera views without interrupting other operations (see also Figure 10).

3.3 Modes of information presentation (feedback)

The list of individual feedback functions resulting from the analysis presented in Section 3.1 above is provided in Table 12 in the appendix Section 7.2. Below, we discuss the functions already implemented in part or in full in the state of the art, followed by a description of all proposed novel implementations.

3.3.1 State of the art

In this section, we briefly cover how the feedback functions considered that are currently fulfilled by snowgroomers are implemented. This will serve as a baseline for quantifying proposed improvements in our envisioned interactions described in Section 3.3.2 below. It will also serve as a specification for implementation of unchanged control functions that need to be included within the playable demonstrations.

Operators rely on visual inspection, feedback from maintenance staff and information from the vehicle dashboard to assess the safe state of the machine (FR11). Operators rely on the sound of the engine and responsiveness of track controls to assess successful engine start (FR12).

To manipulate the blade and tiller, operators rely on visual line of sight to the blade through the windshield, and line of sight to the tiller through rear view mirrors and, when it is available, a rear-facing camera showing a video stream on the in-vehicle display (FR19, FR111). This rear view also allows them to assess the success of repairs made to a damaged slope (FR117, FR119, FR123, FV14, FV15). The blade alignment can also be visualized in on-board software systems such as that shown in Figure 11.

Currently, operators may have access to a 3D visualization of the vehicle on a reconstructed terrain model based on snow depth measurement and GNSS data (see Figure 11). This scan of the immediate vicinity can help navigation and operation (FR116, FR125).

Figure 11: Leica iCON alpine snow measurement visualization system[1]

Furthermore, the snow depth measurement system can be used to notify the operator of excess snow digging depth, in addition to direct line-of-sight to the terrain in the vicinity.

Regarding winch operation, currently, operators know that the winch is successfully anchored at the moment they anchor it, and assume it remains so when the anchor is out of sight (FR130). The torque exerted by the winch motor is indicated to the operator on the in-vehicle display (FR131).

3.3.2 Envisioned feedback functions

3.3.2.1 Inform operator of safe machine state or pending maintenance. (FR11, FR13)

The operator can actively monitor safe machine state using the vehicle diagnostics system which indicates one of two possible states: safe or unsafe (CR12). The information needs to be provided an in intuitive and not disturbing or distracting way to the human operator, causing him to look away from the task at hand. Of course, there is the Graphical User Interface (GUI) available inside the cabin. The GUI can be used to provide information to the operator regarding the safe machine state. The important question here is how to provide this information to the human operator. A possibility could be to highlight the GUI with a specific color (e.g., green for safe machine state, yellow for warning and red for danger), or provide other information in a graphical way (see Figure 12). Another possibility is to display the information on the windscreen, instead of the GUI, having it directly in the view of the operator, potentially without distracting the operator from its tasks. As the hardware for the latter system is not available, such an implementation would have to be done entirely in simulation (see Section 3.4.3)

Figure 12: Suggested highlighting of the GUI

[1] Source: Leica Geosystems https://leica-geosystems.com/products/machine-control-systems/leica-icon-alpine

In the case of warnings for pending maintenance, this is information that doesn't need to be provided to the operator in a continuous way, but can be provided to the operator at the start of the machine, or when the machine is turned off. If a continuous reminder is used, it can be very frustrating to the operator and can distract him/her from his/her tasks. This information can be provided on the GUI (or potentially in the windscreen), at the start of the action and can be accepted by the operator.

In addition to visual feedback, deadman switches coupled with vibrotactors embedded respectively in the track controls and primary joystick could be used to alert the operator to an unsafe machine state if he or she attempts to operate the machine (see Figure 13).

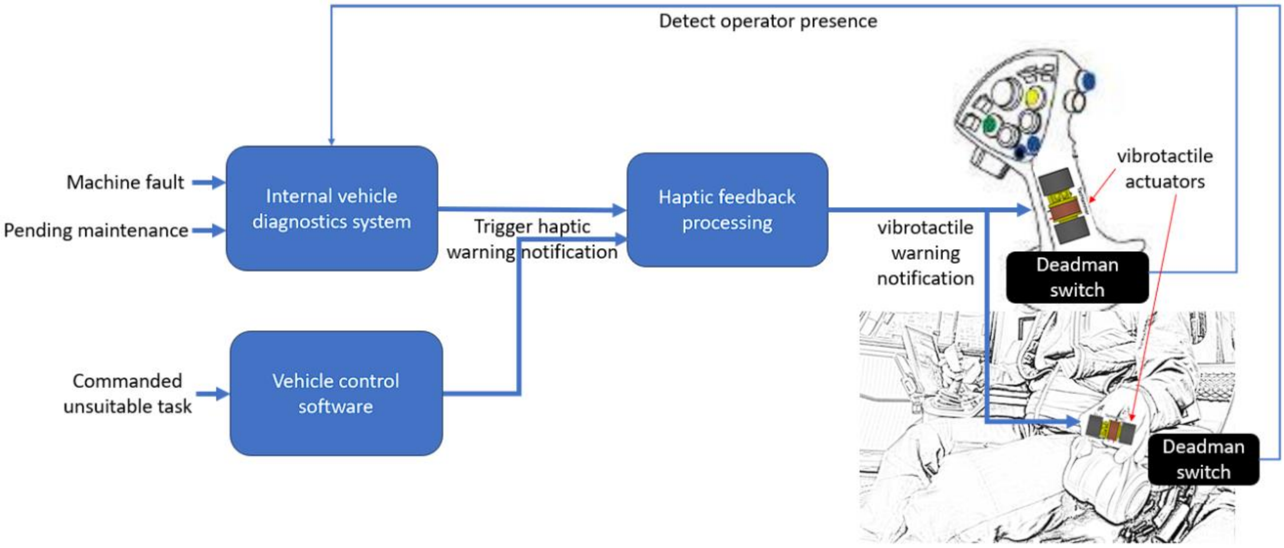

Figure 13: Proposed vibrotactile notification system for warnings

The Texas Instruments DRV2605 haptic driver [3] provides a set of 116 standard haptic effects which could be used as a prototyping library for providing informational and warning cues to operators.

Conversely, according to interviews conducted during operator workshops in Sterzing, providing vibrotactile notifications of a machine safe state is not desirable as this would simply add to informational noise the operator is subjected to. The approach to follow when designing tactile notifications should strictly adhere to a "*no news is good news*" philosophy and focus solely on notifying of safety-critical faults in the system.

3.3.2.2 Inform operator about successful engine start (FR12)

Similar to providing information about the safe machine state, the engine start information needs to be provided to the operator in an intuitive and informative way, without distracting the operator from the task at hand. Potentially, this can be combined with the safe machine state, if a successful engine start was accomplished, the snow groomer can be in a safe state, which can be visualized on the GUI. Additionally, displaying the information in the view of the operator (e.g., windscreen) would be an interesting feature.

Haptic feedback indicating successful engine start will not be considered based on conclusions drawn in Section 3.3.2.1.

3.3.2.3 Inform operator of unsuitable state of vehicle for intended use. (FR14)

Similar to providing information about the safe machine state, the unsuitable state for intended use needs to be provided to the operator in an intuitive and informative way. As this is, to a certain extent, an important state, it should clearly be communicated to the human operator, potentially even distracting the operator from the task it wants to perform. This can be either again on the GUI, clearly informing the operator of the unsuitable state, or also again potentially in the windscreen, so that it is directly in the view of the operator. Additionally, a sound could be provided informing the operator of the unsuitable state of the intended use.

As such warnings should be intrusive, they are a good use-case for vibrotactile feedback as described above (see Figure 13).

3.3.2.4 Inform operator about vehicle width (FR15)

The operator can be informed about the required width of the vehicle by projecting lines in front of the vehicle with the laser projector into the actual environment. The fundamental requirement to correctly project the width is that the projector is correctly registered with regards to the vehicle and the width of the vehicle is known.

This feedback can be implemented in different levels of complexity. For instance, the laser projector could naively project the known width of the vehicle with two parallel straight lines. A more sophisticated method would incorporate the current pose of the vehicle, which can be retrieved by processing Controller Area Network (CAN) bus data. With this, the laser projector could extrapolate the required width of the future path, by assuming a constant pose for a predefined amount of future timesteps. Given a 3D environment and a fully localized vehicle, the projected width lines can furthermore be modified such that they appear undistorted for the operator in the vehicle.

With all suggested modes, the color and strength of the lines can be adjusted to seamlessly integrate the information into the scenery.

3.3.2.5 Inform operator about vehicle alignment (FR16)

The laser projection system can be used to inform the operator by projecting e.g. a warning sign on the surface in front of the machine to raise awareness, if the vehicle alignment is suboptimal. The color scheme might be adapted to the severity of the alignment issue, given a predefined color scheme like a traffic light to properly communicate on the level of urgency. Because the laser projector is configurable in terms of the projected vector graphics, any known regular street sign can be basically projected in a given color mode, in addition to blinking visualizations or even limited animated graphics. Similarly, the spotlight might just cast a colorful light blob in front of the machinery to follow a similar intent concerning the urgency level of the information or warning.

Assuming a target alignment for the vehicle can be computed on the basis of vehicle positional data (GPS and SLAM or similar approaches using computer vision), it could be possible to guide the operator towards the desired alignment using force feedback in the track controls. Discussions with operators during the workshops indicated that such feedback must imperatively be co-located with the control function being executed. That is, force feedback related to steering should be provided on the steering organs if at all, and not e.g., on the primary joystick.

A possible approach would be to provide a light torque based on the error between the current track control position and the track control position that would be required to guide the vehicle towards the target alignment while maintaining its current velocity (see Figure 14). Should the vehicle be immobile (Figure 14 left), this would guide the operator towards a rotation on the spot, whereas if the vehicle is moving (Figure 14 right), this would servo the vehicle's alignment towards the target alignment while continuing motion.

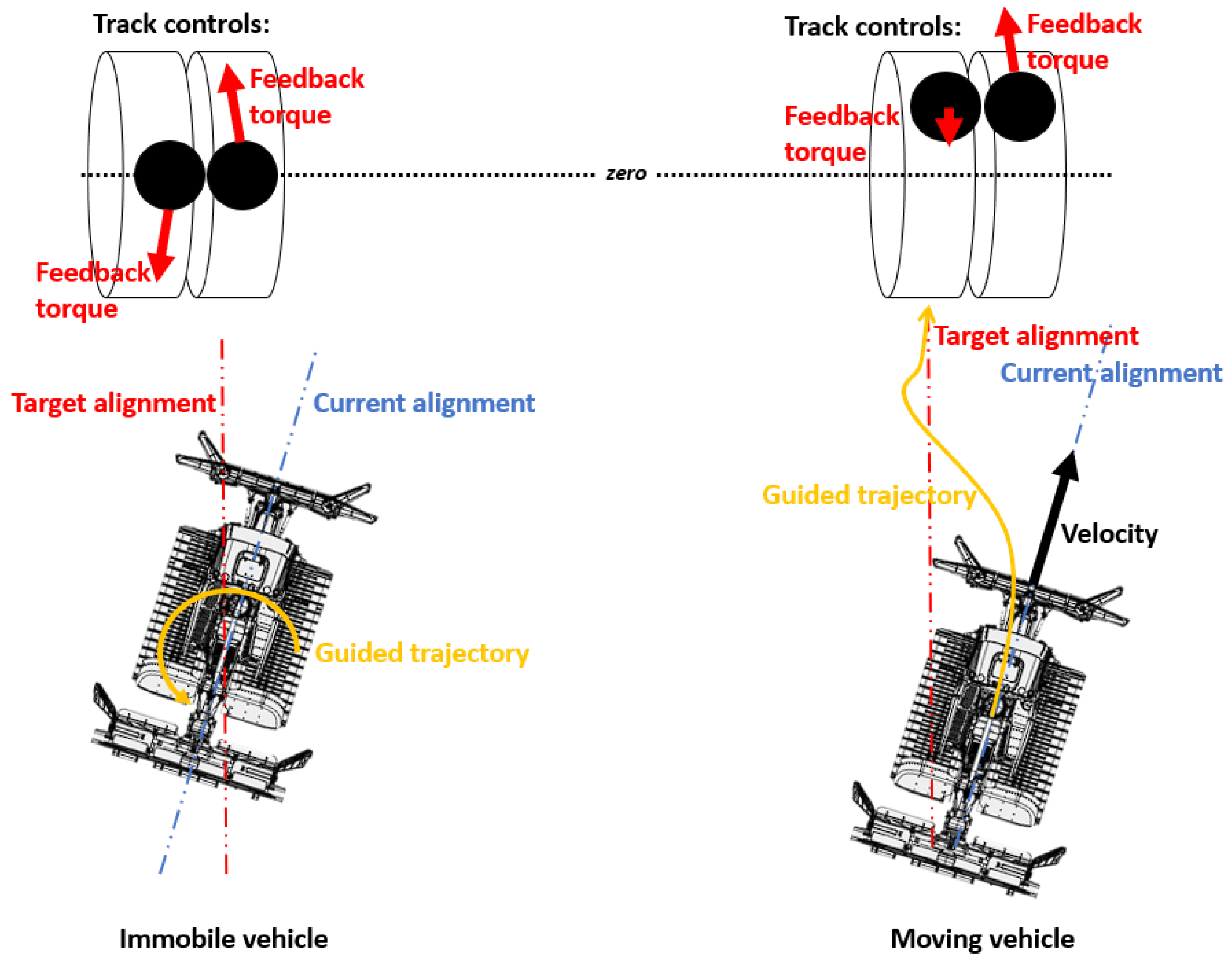

Figure 14: Possible approach to track control torque feedback for guidance

This form of feedback is conditioned on the feasibility of creating track controls capable of providing torque feedback within the THEIA^{XR} project. Also, for safety reasons, it is essential that the operator be able to easily override this guidance, therefore the correct choice of maximum feedback torque is paramount. An additional level of comfort could be achieved by allowing this feature to be toggled, so that operators may only activate it during tricky maneuvers where the assistance could be most helpful.

3.3.2.6 Inform operator about ideal route to work area. (FV12)

Depending on the severity of the alignment issue (respectively the deviation in position and orientation), the system can visualize an optimized trajectory or path to the operator while the vehicle is in motion. Based on the assumption that the vehicle alignment is off the ideal path, the system might show either a suggested trajectory in terms of projected arrows to return to the optimal position or visualize instructions to align the vehicle orientation by marking waypoints in the vicinity of the vehicle, until the vehicle is back to its intended state. Depending on the severity of the alignment issue, the system can also change the color scheme of the laser projections in terms of a traffic-light-like notification of urgency (e.g. red for severe, yellow for less critical, greenish for plausible).

The concept of force feedback in the track controls presented in Figure 14 could also be applied to guiding the operator towards a target location. In this case, onboard GPS sensors coupled with a predefined target and path planning software would generate the heading error values used as inputs for computing the feedback torque on the track controls.

3.3.2.7 Inform operator of location of work area and that work area has been reached. (FR17, FR18)

The exact position of the machine can be provided through GNSS, which provides an exact position. Additionally, a graphical representation of the slopes is available to the human operator. Certain areas are identified on this graphical representation, which are the working areas for human operators. Based on the current position of the snow groomer and the defined working areas, it can be defined if the area has been reached. This information can be communicated via the GUI, making the human operator aware that he has reached the specific position. The operator can be informed by highlighting information on the GUI, informing that the working area has been reached. Additionally, information in the windscreen could inform the operator.

3.3.2.8 Inform operator about current blade settings and state (FR19)

The information that can be retrieved about the blade settings and state is the blade pose and its velocity setpoint, as well as potential information about the pressure in the different actuating hydraulics. Some or all of this information could be communicated via the GUI. Potentially, the GUI could switch to immediately show whenever these settings are modified, providing direct information to the operator. Additionally, real-time information on the windscreen could inform the operator.

3.3.2.9 Inform operator about current tiller settings and state (FR111)

The information available for the tiller is identical to that of the blade, with the addition of information about tiller rotation settings. This information could thus be communicated similarly via the GUI, informing the human operator about the tiller settings and state.

3.3.2.10 Inform operator about discrepancies between current settings and optimal calculated system parameters. (FR110, FR112, FR115, FR116)

Assuming it is possible to calculate optimal blade settings based on the current location and task at hand, this information could be communicated via the GUI, informing the human operator about the current and optimal settings side by side and highlighting differences. As mentioned previously, this information could also be displayed directly on the windscreen.

However, discussions during operator workshops tended to indicate that calculating ideal tiller parameters based on a given situation is a rather unrealistic expectation, and even if this were possible operators would favor automation of the tiller settings rather than information feedback. This opinion was not mirrored when it comes to blade settings, where operators are much more open to feedback regarding settings, in particular haptic feedback. The latter could particularly be helpful for avoiding the ground and too shallow cutting of the snow.

Based on the calculated snow depth and terrain model, it would thus be possible to estimate an ideal blade pose at any given time. From this, two forms of force feedback on the primary joystick may be imagined (see Figure 15 below):

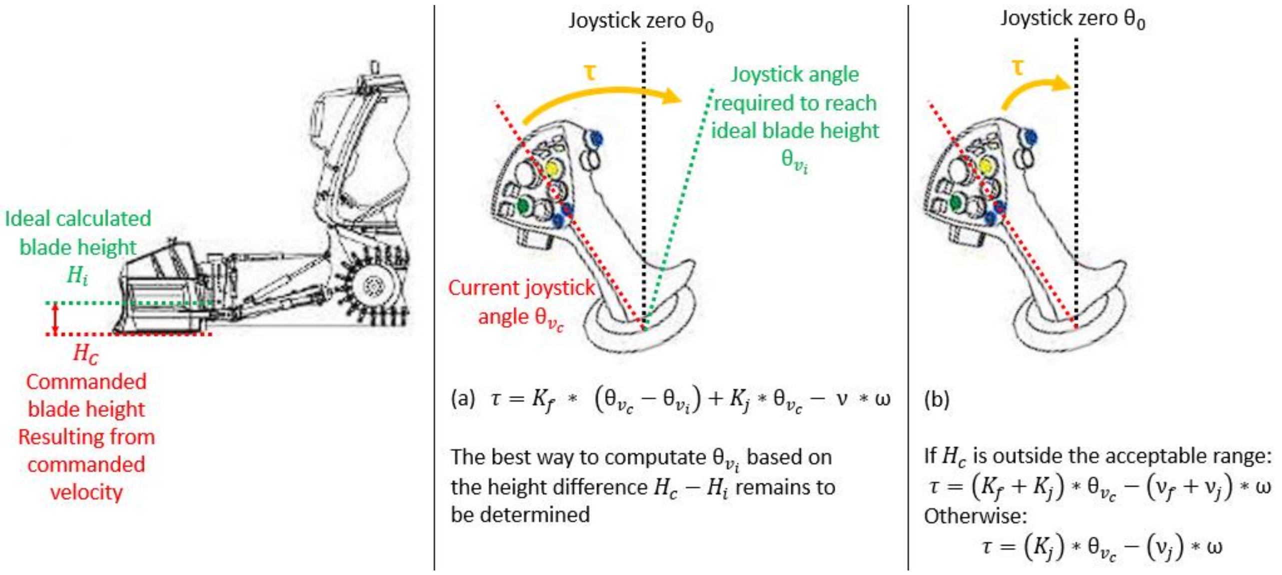

Figure 15: Two approaches to force feedback for blade pose correction

(a) Attractive virtual fixtures: A low stiffness virtual damped spring on all joystick axes gently pulls the operator towards the calculated optimal position by generating a torque τ. On top of the joystick's base stiffness K_j, the operator thus feels an added stiffness K_f. The total felt damping ν resisting the angular joystick velocity ω may be the joystick's base damping or also include an optional added damping.
(b) Repulsive virtual fixtures: The operator is free to manipulate the blade within an acceptable region, feeling only a torque resulting from the joystick's base stiffness K_j and base damping ν_j,. However, any motion outside of this region is met by an increase in joystick stiffness (added K_f) or damping (added ν_f), informing the operator that the current blade settings are outside the recommended range and preventing excessively fast motions outside of the recommended range. In this case however, the joystick still pulls the operator towards the zero position (commanding a null velocity) and thus does not offer any active correction of the blade pose.

For safety reasons, it is imperative that the operator still be able to move the blade outside of the recommended or ideal calculated pose. Therefore, correct choice of stiffness and damping are essential.

3.3.2.11 Inform operator about recommended speed. (FR113)

Based on the velocity of the snowgroomer, which is provided by the internal software of the snowgroomer, and its current position on the slope and in the working area, provided by the GPS information, a recommended speed can be provided to the human operator. This recommended speed can be depicted on the GUI, in the area where the current speed of the snowgroomer is depicted. The recommended speed can be highlighted on the GUI and through that, the operator can try to speed up or slow down to the recommended speed.

The haptic feedback idea proposed in Figure 14 above could very well be used to guide the operator towards setting an ideal calculated speed, if the vehicle onboard GPS, IMU and terrain model allow such a velocity to be computed. An alternative approach involving vibrotactile feedback in the track controls such as described in Figure 13 above could be to only provide a vibration warning notification to the operator in the event where the current speed is too high and deemed unsafe given the environment model and measured snow and weather conditions.

3.3.2.12 Inform operator about insufficient slope quality or damage to slope (FV14, FR117)

Assuming that there is a way to accurately detect insufficient slope quality (e.g. from image processing on the video stream provided by the vehicle's rear-facing camera), the vehicle onboard software could trigger "insufficient slope quality" warning notifications that may be fed back to the primary joystick's built-in vibration actuator (see concept described in Figure 13).

3.3.2.13 Inform operator about recommended tiller pressure. (FR114)

The display provides information about the tiller pressure. Based on information coming from the internal software in the snowgroomer, information will be provided on the display (or potentially even in the windscreen) to optimize the pressure on the tiller. The recommended amount of pressure can be visualized (graphically) on the display and, in combination with the haptic joystick, the operator can increase or reduce the pressure and as soon as the recommended pressure is reached, the GUI highlights this.

3.3.2.14 Inform operator about bumps and obstacles in poor visibility conditions. (FR122)

Using the laser projector, a grid can be projected at the vehicles surrounding. The grid's granularity and therefore its capability to yield information to the operator is dependent on the laser hardware used. With standard laser projectors, only a 4x4 grid would be feasible to be projected over the whole field of view. However, the finer the grid, the more apparent smaller bumps and obstacles are.

3.3.2.15 Inform operator about successful activation of the "poor visibility support" (FR120)

The GUI informs the operator that the poor visibility support has been successfully activated. This could potentially be done by changing the layout of the GUI, informing that the poor visibility support is activated. Ideally, this would also be displayed in the windscreen.

3.3.2.16 Provide a 3D visualization of vehicle and slope to operator (FR125)

Beyond providing only a 3D visualization of the snow depth and terrain in the vicinity of the vehicle, it may be interesting to provide a 3D visualization of the wider surrounding area and accurate 3D representation of the vehicle itself in order to help operation in zero visibility. This means the vehicle model needs to be in exact scale, with all attachments set as per the current known states of the real attachments. Furthermore, a more comprehensive terrain model incorporating e.g., obstacle data would need to be available.

3.3.2.17 Inform operator about obstacles in the vicinity. (FR126, FR127, FR128)

The GUI, in combination with sensors and obstacle detection, can display potential obstacles in the vicinity of the snowgroomer, combined with their distance to the machine. Ideally, this could also again be displayed in the windscreen.

In the event where the snowgroomer is detected as being on a collision course with an obstacle, vibration pulse trains with a frequency inversely related to the distance to the detected obstacle could be provided via the track controls (see concept described in Figure 13). In the event of imminent collision, this could be augmented or replaced by force feedback in the track controls guiding the operator towards a reversing motion (see also concept described in Figure 14). As previously discussed, tactile or kinesthetic warning cues should imperatively be displayed on the control organ responsible for the associated function, i.e. steering in the case of obstacle avoidance. Hence this feature is contingent on the development of track controls into which vibrotactile actuators are embedded.

3.3.2.18 Warn operator that winch is required. (FR129)

The GUI informs the operator that the winch is required, based on information coming from the snowgroomer internal software. As this is of importance to the operator, this information needs to be provided in an urgent way, being highlighted on the GUI. Potentially, this information could also be displayed in the windscreen.

A vibration warning with a specific pattern could indicate that the use of the winch is required. Since this is a safety-critical function, it could make sense to use rather intrusive vibrotactile feedback.

3.3.2.19 Inform operator about winch cable tension, path and/or direction (FR131, FR132)

The GUI informs the operator that the winch cable tension, based on information coming from the snowgroomer internal software. As this is of importance to the operator, this information needs to be provided in an urgent way, being highlighted on the GUI. Potentially, this information could also be displayed in the windscreen.

The laser projection system can be used to display warning signs in the projection area in front of the machinery, respectively the operator, to communicate warnings or other related information with respect to the winch. It can also be used to draw textual information in a limited amount to communicate, e.g. numbers like percentages or directions. Similarly, arrows can be used to indicate directions or paths. The color scheme can be adapted to indicate urgency.

3.3.2.20 Environment warning system (FR135, FR136)

The successful activation of the warning system, can be highlighted to the operator by e.g., changing the color configuration of the display. As depicted in Figure 16, the display could be highlighted in a color that is explicitly assigned for the environment warning system. If the highlight is active, the operator can assume that the warning system has been successfully activated (FR135).

To inform the operator that persons are in the vicinity of the danger zone around the snowgroomer, a potential warning could be that the display is informing the operator by highlighting (e.g., blinking) the side where the danger zone has been violated. If something enters from the right, the right side of the display will perform a blinking action (FR136).

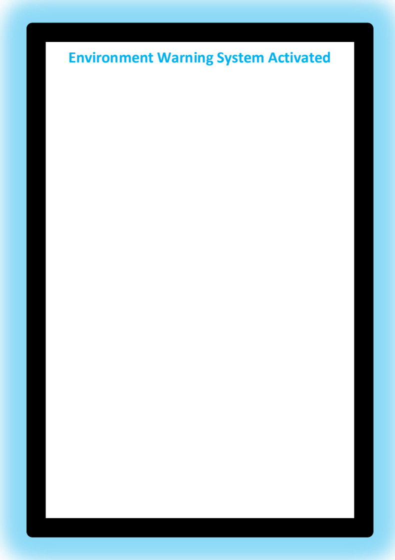

Figure 16: Display with environment warning system activated

The laser projector mounted on the vehicle can be used to cast a set of lines into the field of projection. Depending on the mounting options of the laser projector, which are targeted to the front for the operator only in a standard scenario, this is restricted to the projection area in front of the vehicle. However, similar projections can be considered around the entire vehicle, given a variable number of projectors mounted at respective plots on the vehicle. The projection of a line can be augmented with, e.g., multiple spaced signs like the exclamation mark sign. In addition to changing the respective color schemes, the projections can be static or blinking and either denote a fixed area or radius around the machinery (projector-centered), or located in world space (world-centered).

3.3.3 Feedback functions not yet considered

Table 3 below recaps the feedback functions are neither dealt with in the state of the art (Section 3.3.1), nor in the partner proposals (Section 3.3.2). For these, a decision will have to be made to either propose implementations or to ignore them in the future demonstrators.

KEY	FEEDBACK FUNCTION
FR118	Inform operator about available excess snow to be used for repairs.
FR121	Inform operator about vehicle dimensions relative to slope in poor visibility conditions.
FR124	Inform operator about the horizon location and orientation in poor visibility conditions.
FR130	Inform operator about successful winch anchoring.
FR133	Inform operator about a hazard in winch operating area.
FR134	Inform operator about the direction towards or location of a hazard in the vicinity.
FR137	Inform operator about progress on or completion of planned work.
FV11	Provide operator with a view "through the snowgroomer's eyes"
FV12	Inform operator about ideal route to work area.
FV13	Inform operator about progress along a route.

Table 3: Summary table of feedback functions for UC1 which are missing implementation concepts

3.4 UC1 Demo specification

The playable demonstration for the snow grooming use-case will be developed under the heading of Creanex, who are in the process of building a virtual environment capable of hosting both physical and simulated UI elements showcasing the control and feedback functions previously discussed.

This section begins by presenting the virtual environment and vehicle as well as giving an overview of the simulated sensor data that may be available in this environment to feed into the UI elements considered. We then separately discuss the physical UI elements that will be required for interacting with this demo, based on work from deliverable D5.5. To completely cover the spectrum of control and feedback functions we wish to evaluate, it will also be necessary to simulate certain UI elements, which are discussed in a later section. Finally, we recap the sequence of actions and events from the deliverable D3.2 scenarios that we plan to use as the simulation scenario.

3.4.1 Virtual environment, vehicle simulation and sensor data simulation

The snow groomer simulation is based on the Creanex simulator platform. The virtual working environment, the simulation scene, has been created from real slope data provided by Prinoth. The terrain data model was converted into a ".fbx" file, which was then imported into Unity editor and further developed to be a so-called Unity terrain, see Figure 17.

The physics simulation is based on rigid-body dynamics including interaction with the environment meaning that there are contacts between the machine and the ground and on each contact point there is a pair of forces based on which the machine moves.

Figure 17: Prinoth snow groomer in simulated environment

The top-level architecture is presented in Figure 18. The interaction models used by the physics simulation are converted or manually created from the visual models. Control panels are used to operate the machine in physics simulation. After every simulation step the state in physics is updated to the visualization system.

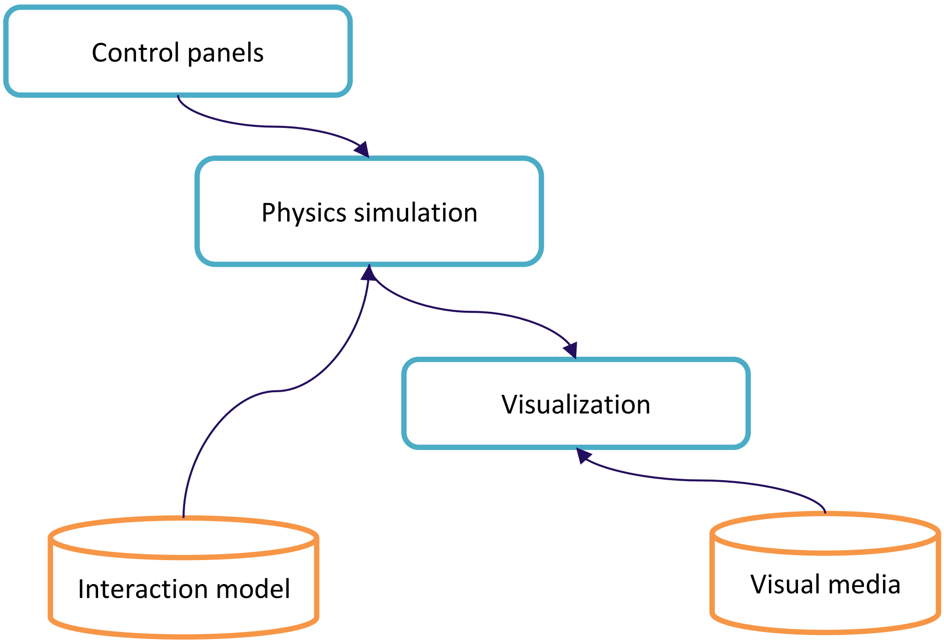

Figure 18: Architecture of the Creanex simulator platform.

The Creanex simulation platform and available features for sensor simulations and other capabilities are presented in deliverable D4.5.

3.4.2 Physical UI elements

The functions described above in Sections 3.2 and 3.3 will make use of physical touch-screens provided by TTC (see Figure 19) as well as the novel 6DoF haptic input device developed by HAP. A concept for a prototype of haptic-enabled track controls could also be tested by HAP to evaluate certain proposals above if they are retained after task T3.2 concludes. The physical hardware interfacing with the simulation is described in detail in deliverable D5.5.

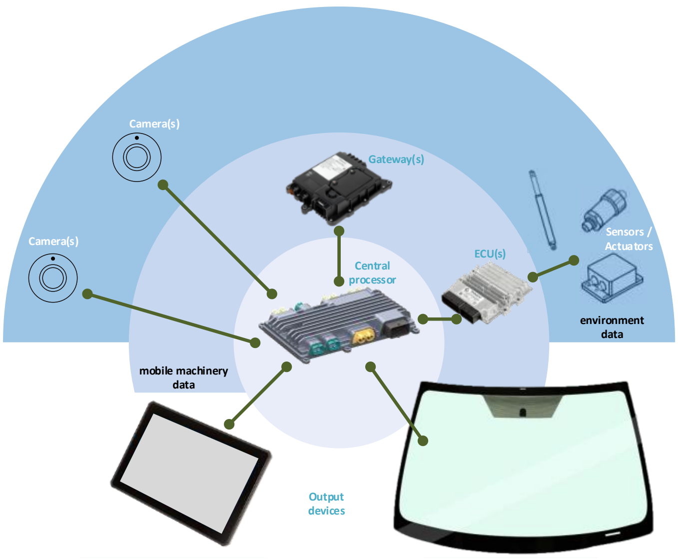

Figure 19: Collecting, processing and displaying of information

3.4.3 Simulated UI elements

The entire hardware setup is controlled by the Unity3D game engine, which, in turn, is fed by data about the environment in the form of a preexisting 3D model and telemetry data from a machine. Based on this recorded data, the simulated laser spotlight projection is configurable concerning the projected content, which is based on vector graphics, as opposed to pixel graphics used for regular video projectors. The content, as well as the placement, color and respective projective distortion (or undistortion) can be configured directly in the game engine. Similarly, the spotlight is modelled as a torch light in the Unity3D game engine and can be controlled by similar measures, such as color, direction of light casting. Both entities are rigidly mounted on the virtual vehicle, such that any simulated movement of the vehicle automatically drags the respective laser projection and spotlight entities with it.

As mentioned above, UI projections on the vehicle windscreen would also have to be implemented entirely in simulation given that the required hardware for a physical implementation will not be available in the D5.5 hardware platform.

4 Use-case 2: Reachstacker

4.1 Scenario analysis

Once again, task T3.2 provided a set of two scenarios for the logistics use-case: a "*realistic*" scenario focused on control and feedback functions implementable in-vehicle in the short term, and a "*visionary*" scenario focused on a more long-term perspective of a potentially teleoperated vehicle. However, given the short-term focus of our logistics partners on moving to remote-controlled (RC) reachstacker operation, these scenarios were adapted to form a "*realistic RC*" scenario and a "*visionary RC*" scenario. Because of the significant overlap between tasks in the scenarios we present the component tasks for the "*realistic RC*" scenario in full in Table 4, followed by a shorter description of how the "*visionary RC*" scenario deviates from it in Table 5.

Scenario section	Component task
Matias logs into the system by entering his username and password on the login screen.	**Control:** Operator logs into the RC console system / Operator identifies himself in the RC console system. **Feedback:** Inform operator of successful log-in **Feedback:** Inform operator of the operator ID recognized via the token.
Matias subjects the RC desk to his inspection. He first checks with the push button that the RC desk indicator lights are working.	**Control:** Operator checks that the RC console indicator lights are working. **Feedback:** Inform operator of functional RC console indicator lights.
In case of malfunction, he contacts service personnel.	**Control:** Operator contacts service personnel. **Feedback:** Provide audio communication to service personnel.
Then Matias activates the RC console by using the ACTIVATE button, and a new connection between the console and a reach stacker (RS) is established.	**Control:** Operator activates the RC console in order to establish the connection to the reach stacker **Feedback:** Inform operator of successful activation of the RC console **Feedback:** Inform operator of successful connection to the reach stacker **Feedback:** Inform operator of preset vehicle settings associated with recognized operator ID **Feedback:** Inform operator that personalized vehicle settings have been successfully applied.
The system displays the machine operation view.	**Feedback:** Provide Operator with machine operation view.
Because it is already dark, Matias switches the working lights of the RS ON by pressing the working lights button on the touch panel.	**Control:** Operator switches on the working lights of the RS. **Feedback:** Inform operator that RS working lights are switched on
The reach stacker is subjected to the first inspection of the day (e.g. tires, oil or fuel leaks and whether the engine oil level is sufficient). At the parking area, the maintenance person checks the machine visually.	**Control:** At workshop or parking place, the maintenance person checks the machine visually. **Feedback:** Inform operator of vehicle operational state. **Feedback:** Inform operator of vehicle safety.
Matias starts the operation with RC desk and starts the engine. He checks the status of the machine from	**Control:** Operator starts the engine

the PC screen and videos. Matias visually checks snow and tires via camera feed and PC screen. (The system alerts Matias only if the oil level is not sufficient.)	**Control:** Operator checks the status of the machine from the PC screen and videos **Feedback:** Inform operator of successful engine start **Feedback:** Provide multiple camera views of vehicle in parking area.
Then Matias switches the reach stacker to auto mode. The reach stacker steers itself out of the parking area.	**Control:** Operator switches the machine to auto mode. **Feedback:** Inform operator of successful activation of auto mode **Control:** The machine steers itself out of the parking area.
Matias looks at the PC screen, which displays information on the assigned orders on the job introduction screen. Matias selects the next job.	**Control:** Operator checks job information. (tentative: may not require operator's input) **Feedback:** Inform operator about list of assigned orders and pending jobs **Control:** Operator selects job and the status of the machine and video screens **Feedback:** Inform operator about successful selection of a job. **Feedback:** Inform operator of the current job details and overview.
Matias focuses on the video feed from the cameras projected onto the monitor screens, while the RS automatically drives to the destination.	**Control:** Drive machine to target location **Control:** Operator triggers emergency stop
Matias does not yet know the layout of this part of the port by heart, but the system provides the information on PC screen and the video feed from the cameras.	**Feedback:** Provide operator with the layout of the port in the vicinity of the vehicle / in the job area **Feedback:** Provide operator with camera views to the vicinity of the vehicle
At one point, the system gives a warning of an approaching machine. Matias notices on the rear camera video feed that a colleague is driving his reach stacker directly behind him, before he takes another turn and disappears behind a stack of containers.	**Feedback:** Alert operator to approaching machine **Feedback:** Provide rear camera view to operator
The machine arrives at its destination. The machine approaches the container from the front. Matias checks on the video screens and AR overlays that there is enough room for extending the spreader and begins to move the spreader into a suitable working position.	**Control:** Operator checks for safety before moving the spreader. (tentative: this may not require operator input) **Feedback:** Inform operator about safe space available for extending spreader
He chooses the appropriate spreader size by pressing the spreader length button on the touch panel.	**Control:** Operator controls the spreader size. **Feedback:** Inform operator about current set spreader size
He lowers the spreader down towards the container by using the joystick to control the hoist and adjusts the skew using the skew/micro movement joystick.	**Control:** Operator moves and extends spreader. **Feedback:** Provide operator with unobstructed view towards spreader and container
The remaining horizontal and vertical distance between the spreader's twist locks and the corners of the container are visualized on the video screens with AR overlays.	**Feedback:** Inform operator about remaining horizontal and vertical distance between twist locks and container corners
He engages the twist locks with the press of a button on the joystick. The light indicators on the spreader tell	**Feedback:** Inform operator that twist locks can safely be engaged **Control:** Operator engages twist locks.

him that the twist locks are being safely locked. This allows him to lift the load.	
Matias now has to start reverse movement and checks monitors' video feeds to make sure his route is clear.	**Feedback:** Provide view of the vicinity including potential obstacles to operator **Feedback:** Inform operator that vicinity is clear for reversing. **Control:** Operator triggers reverse movement
The machine now makes its way to a corridor between the container stacks where it is supposed to load the container onto a truck trailer. (The direction of the loading area is also indicated on the video screen.)	**Feedback:** Inform operator that boom and spreader are in a suitable position for driving.
The system identifies with cameras the truck driver from the video feed by the license plate number that was transmitted via the order. The machine now approaches the trailer for loading up the container.	**Control:** The system checks truck license plate with OCR. **Feedback:** Inform operator about truck ID in loading order **Feedback:** Inform operator about ID of truck currently being loaded
The machine is switched to RC mode.	**Control:** Operator switches the machine to RC mode **Feedback:** Inform operator of successful switch to RC mode
Matias positions the spreader with the attached container above the trailer.	**Feedback:** Inform operator about ideal loading position and orientation relative to truck being loaded. **Control:** Operator aligns the stacker with trailer position.
He lowers the container and makes fine adjustments using the skew/micro movement joystick. Matias uses the camera views and AR overlays to check the correct placing of the container.	**Feedback:** Inform operator of discrepancies between container actual and ideal position for loading.
As the container is lowered onto the trailer, Matias disengages the twist locks by pressing a button on the joystick and lifts the spreader again.	**Feedback:** Inform operator that container has been sufficiently lowered to allow release. **Control:** Operator disengages twist locks. **Feedback:** Inform operator that twist locks have successfully been disengaged.
(While the truck driver walks around the trailer to check the container locks in all four corners, he is highlighted on the video screen.)	**Feedback:** Inform operator that spreader has cleared the container. **Feedback:** Inform operator of the presence of persons in the vicinity of the vehicle
Matias waits until the driver has signaled that everything is fine, then the machine is switched to auto mode and it can head to its next job. Matias is checking the camera's video feeds and system status as the machine reverses automatically.	**Feedback:** Provide operator with clear vision and earshot of the vehicle vicinity **Feedback:** Inform operator that vicinity is clear for safe reversing.
While approaching the container head-on, Matias adjusts the spreader by pressing a pre-set button on the touch panel, extending the spreader to its widest configuration.	**Control:** Operator extends spreader (could be manually extended or toggled between two modes). **Feedback:** Inform operator that spreader has reached a preset position.
The system selects the views for Matias for a better view of the twist locks of the wide container.	**Control:** The system adjusts camera views. **Control:** Operator adjusts cabin position. **Feedback:** Inform operator of current camera position.

	Feedback: Inform operator that ideal or desired driver cab position has been reached
As soon as the position of the camera views are right, the machine is switched to RC mode and Matias can lower the spreader in a suitable position so that the AutoLock function can be carried out.	**Feedback:** Inform operator that spreader has reached suitable position for picking container **Feedback:** Inform operator that spreader has been sufficiently lowered to allow AutoLock function to run **Control:** Operator triggers AutoLock function. **Feedback:** Inform operator that AutoLock has successfully been carried out. **Control:** Operator maneuvers spreader and boom.
Matias lifts the container as soon as the green light is visible. He maneuvers the spreader and boom back into a suitable position for transport, ...	**Feedback:** Inform operator that container is ready to be lifted **Feedback:** Inform operator that the boom and spreader are in a suitable position for transport.
For his scheduled break, Matias disconnects the RC table from the RS. First, he must check that the job is completed and the RS movements have stopped (there is also a delay for disconnection which assures that the CHE movements have stopped), and that the joysticks are released to the neutral position. Once he has checked these, and seeing that that the light on the DISCONNECT button is on (indicating that it is possible to disconnect), he pushes the DISCONNECT button.	**Feedback:** Inform operator that the job is complete **Feedback:** Inform operator that RS is safely stopped and ready for disconnect. **Control:** Operator disconnects RC console from reachstacker **Feedback:** Inform operator that RC console is disconnected from reachstacker

Table 4: Scenario analysis for the UC2 "realistic RC" scenario

Below is the table highlighting the differences in the "*visionary RC*" scenario:

Scenario section	Component task
The system can automatically adjust the RC desk according to his personal settings for the seat height and dashboard view (icon placement etc.). He selects his assigned harbor terminal and vehicle for today's job, which is located at a small port in southern Finland.	**Control:** Automatic adjustment of seat height etc. based on personal settings. **Feedback:** Inform operator about assigned harbor terminal. **Control:** Operator selects assigned harbor terminal. **Feedback:** Inform operator about selected harbor terminal. **Feedback:** Inform operator about assigned vehicle. **Control:** Operator selects assigned vehicle. **Feedback:** Inform operator about selected vehicle.
Matias starts the safety inspection by switching to the outside view, facilitated by several cameras installed in the vehicle garage.	**Control:** Operator switches camera view. **Control:** Operator triggers vehicle function diagnostics.
Several alternative camera views, a minimap and a dashboard of the vehicle's parameters, such as fuel, oil temperature and the gearbox temperature, are available on the smaller monitor.	**Feedback:** Provide dashboard of the vehicle's parameters (fuel, oil temperature, gearbox temperature)
Matias selects the first job and immediately sees a directional indicator appearing on the screen which shows the ideal route and distance to the target location. Matias does not yet know the layout of this part of the port by heart, but the system displays the optimal path.	**Feedback:** Inform operator about ideal route to target location. **Feedback:** Inform operator about distance to the target location.

While the machine automatically drives to the job site, moving markers on the outer frame of his camera view indicate the relative position and proximity of objects and vehicles moving around him.	**Feedback:** Inform operator about current driving functions being executed (acceleration, braking, steering) **Feedback:** Inform operator about relative position of objects and vehicles in the environment. **Feedback:** Inform operator about distance to objects and vehicles in the environment. **Feedback:** Inform operator about predicted trajectory of vehicles in the environment.
Matias arrives at his destination, which is also indicated by the target container being highlighted in the augmented camera view.	**Feedback:** Highlight target container in augmented camera view.
As he approaches the container from the front, the weight of the container and the XR assistance indicators are being shown on its center.	**Feedback:** Provide operator with AR overlays on video during manual remote driving **Feedback:** Inform operator about container weight.
… until both the laser projections and the light indicators on the spreader tell him that the twist locks are being safely locked.	**Feedback:** Project the container limits on the ground
Matias now has to reverse and checks the rear-view camera and minimap to make sure his route is clear.	**Control:** Operator calls up minimap. **Feedback:** Provide operator with a minimap of the vicinity
The truck is being recognized and highlighted by the system as soon as it comes in view	**Feedback:** Highlight the target truck when in view.
The ideal trailer position for loading is being visualized on the ground, allowing Matias to easily find the ideal alignment to make loading easier.	**Control:** Operator triggers XR assistance **Feedback:** Project the ideal loading position on the ground
While the truck driver walks around the trailer to check the container locks in all four corners, he is highlighted on the video screen/ the outer screen frame and the minimap.	**Feedback:** Display persons in the vicinity on the minimap **Feedback:** Highlight persons in the vicinity in the camera views
To make the transport of the bulky container safer, Matias activates the width visualization function, which enables an XR visualization of the container's outer corners on the ground, helping Matias to estimate the distance he needs to keep from container stacks and other vehicles in the tight corridors of the port.	**Control:** Operator activates width visualization function. **Feedback:** Provide operator with a visualization of the container center of mass. **Feedback:** Inform operator of relative width of vehicle and container to free space in which the vehicle navigates. **Feedback:** Inform operator of optimal path to follow in tight corridors of the port.
Matias sends the vehicle into standby.	**Control:** Operator puts the vehicle into standby **Feedback:** Inform operator that vehicle has successfully been put into standby.
Matias logs out of the vehicle control interface and takes a look at his personal performance dashboard on the monitor, which tells him the number of containers he delivered today, his distance driven, the average time per pick-up and placement process and how his performance compares to his previous workdays. The dashboard tells him that he managed to improve his average pick-up time per container by 5 seconds since last week and by more than 20 seconds since he started working as a professional reach stacker operator just a few weeks ago.	**Control:** Operator calls up personal performance dashboard **Feedback:** Provide operator with a personal performance dashboard (number of containers he delivered today, his distance driven, the average time per pick-up and placement process and how his performance compares to his previous workdays)
Before logging out of the RC desk, Matias takes a last look at the job playback, a feature that shows a fast-forward video visualization of Matias' driving path on the port map.	**Control:** Operator calls up job playback function. **Feedback:** Provide operator with a fast-forward playback of the day's driving path

Matias then logs out of the RC system.	**Feedback:** Inform operator of successful logout of the RC desk.

Table 5: Added functions from the UC2 "visionary RC" scenario

4.2 Availability of control functions (input)

The analysis of the scenarios presented in Section 4.1 above yields the list of individual control functions summarized in Table 13 in the appendix Section 7.3. Below, we discuss the functions already implemented in part or in full in the state of the art, followed by a description of all proposed novel implementations.

4.2.1 State of the art

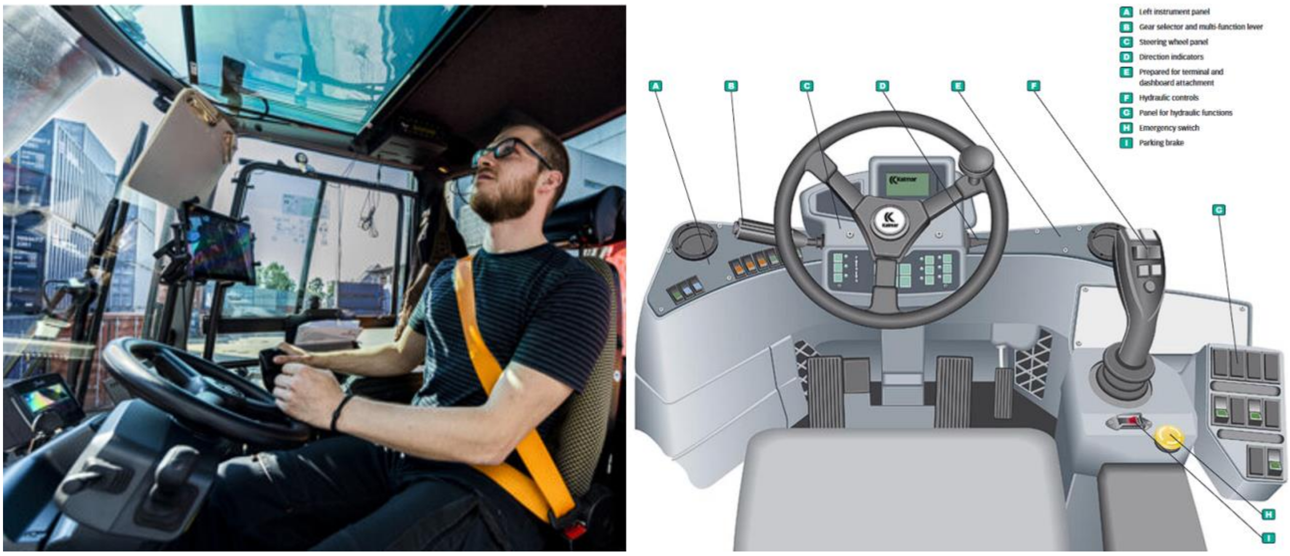

Figure 20: Reachstacker cabin

Currently, reachstacker cabins (see Figure 20) provide operators with key switches to start and stop the engine (CR27) and execute hydraulic functions and various vehicle functions (CR25, CR221, CR226). For driving functions, a steering wheel and pedals allow the operator to maneuver the vehicle (CR210, CR213, CR218, CR222). A joystick provides control over the hydraulics of the boom through joystick rotation (see Figure 21) and of the spreader through a set of four buttons, two for spreader shifting and two for spreader rotation. The twist-locks are actuated thanks to additional buttons on the joystick (CR215, CR216, CR217).

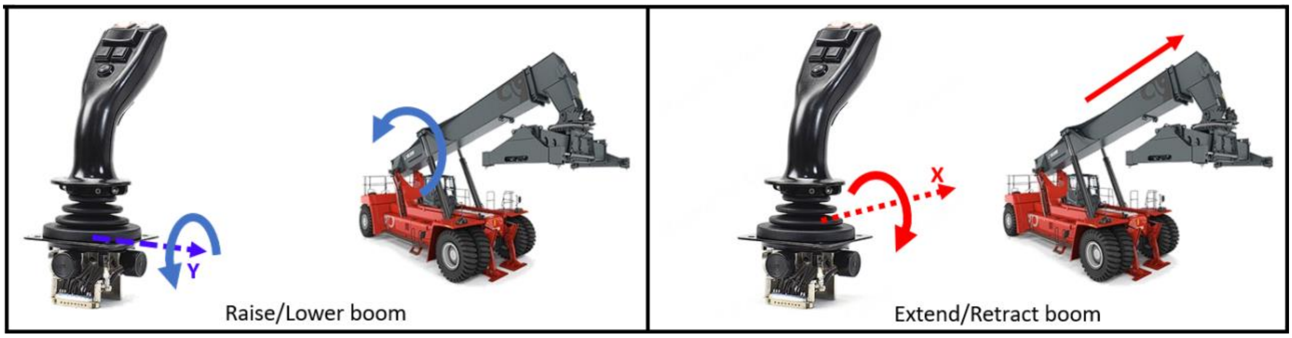

Figure 21: Reachstacker joystick input mapping

4.2.2 Envisioned control functions

4.2.2.1 Operator logs into the RC console system. (CR21)

The operator may log into the RC console by being prompted to enter a combination of password and username via a dialog box shown on the touch panel GUI, using an on-screen keyboard. The login dialog may be displayed immediately on RC console startup or may alternatively be called using a dedicated on-screen button. Alternatively, login could be simplified by using a smart card reader for identifying the operator, thus only requiring a password to be entered.

4.2.2.2 Operator checks that the RC console indicator lights are working. (CR22)

A dedicated push-button on the RC console desk is provided for the operator to check that the console indicator lights are functional. Pressing it activates all the console indicator lights, while depressing it switches them back off, making them available for standard operation (FR22).

4.2.2.3 Operator contacts service personnel. (CR23)

The operator has the opportunity to contact service personnel by connecting headphones to the console and using its built-in microphone.

4.2.2.4 Operator activates the RC console in order to establish the connection to the reachstacker (CR24)

A dedicated “ACTIVATE” push-button on the RC console desk allows connection of the RC console to the reachstacker.

4.2.2.5 Operator switches on the working lights of the reachstacker. (CR25)

Once connected, the RC console touch-panel provides an on-screen “working lights” button. Pressing it triggers the working lights of the remote reachstacker to switch on.

4.2.2.6 Operator starts the engine. (CR27)

By pressing a button on the touch screen which remotely triggers the engine cranking, the RC operator starts the engine if it is not already running and checks the status of the machine from the PC screen and videos

4.2.2.7 Operator checks the status of the machine from the PC screen and videos. (CR212)

The RC operator checks the system safety using the provided camera streams (see CV24) and information from the diagnostics system shown in the UI. Cameras in the reachstacker parking area allow the operator to visually check for snow and the state of the tires. The diagnostics system only alerts the RC operator if oil levels are not sufficient.

4.2.2.8 Operator switches the machine to auto mode. (CR29)

The operator activates auto mode by using a dedicated button on the touch panel. This causes the reachstacker to use its onboard navigation system (GPS and path planner) to drive to the next defined destination. Alternatively, a physical button on the primary joystick could be used to trigger the same function.

4.2.2.9 The machine steers itself out of the parking area. (CR210)

This control function involves automating driving on the basis of positional and proximity sensors and is beyond the scope of the THEIA^{XR} project. In the demonstrators, it will be assumed that this works and the simulation will behave accordingly.

4.2.2.10 Operator checks job information. (tentative: may not require operator's input) (CR211)

The RC operator can use a button on the touch screen interface to call up the job introduction screen (see FR216 and FR218).

4.2.2.11 Operator selects job and the status of the machine and video screens (CR212)

The RC operator can select a job from the list available in the job introduction screen. Selecting a job causes the job details to appear as well as a directional AR indicator to be shown on the PC monitor screen.

4.2.2.12 Drive machine to target location (CR213)

For automated driving, see remark on CR210. For manual driving, the operator uses a set of physical pedals and a steering wheel on the RC console that enable an intuitive driving experience when used in conjunction with the in-cabin camera view (see FR220).

4.2.2.13 Operator maneuvers spreader and boom. (CR215)

The operator uses the primary joystick to operate the spreader and boom. In the event where this joystick operates in the conventional 2DoF mode found in in-cabin operation, the control scheme is identical to the state-of-the-art (see Section 4.2.1). However, the novel haptic input device being developed by Haption could provide additional degrees of freedom to enable simultaneous control of all spreader and boom DoF (see Figure 22).

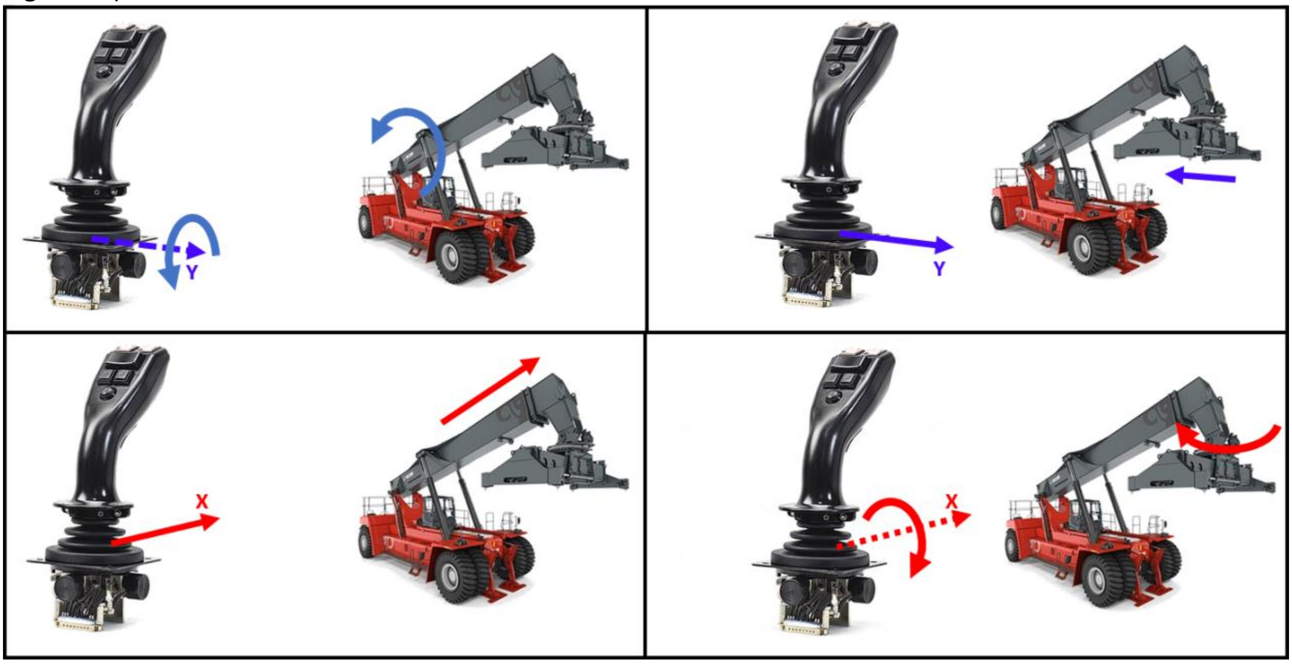

Figure 22: Example of a possible 4DoF joystick motion mapped to all reachstacker DoF

Also, it may be interesting to explore more intuitive mappings of joystick motion to spreader motion such as direct position control of the spreader or container (see Figure 23).

Figure 23: Concept for direct position control of the spreader with a 4DoF joystick

4.2.2.14 Operator moves and extends spreader (CR216)

Fine sideways shifting of the spreader may leverage the novel control mappings proposed above for CR215. A pair of dedicated buttons on the joystick allows toggling between preset sizes if rapidly pressed, whereas continuously pressing them down could map a joystick DoF to manual control over spreader size.

A simplified spreader size toggle could also make use of the job information, i.e., the known preset container width, allowing the operator to use a single button to toggle between the smallest spreader size (for maneuverability) and the preset spreader size for the selected job.

Finally, the RC console touch panel may provide a set of controls for toggling between preset spreader sizes and/or manually controlling spreader size. Of course, control over spreader size is only available when no container is attached.

4.2.2.15 Operator engages/disengages twist locks. (CR217)

Since engaging or disengaging the twistlocks is an action that needs to be executed in close proximity with adjustments to the boom and spreader positions, it is most sensible to provide a pushbutton or toggle switch on the joystick which engages or disengages the twist locks. If the twist lock sensors show no load (no container attached), then this button maps to "engaging the twist locks", otherwise, it maps to "disengaging the twist locks".

4.2.2.16 The system checks truck license plate with OCR. (CR219)

For the purposes of the demonstrator, this function will act similarly to automatic driving (CR210, CR213, CR218) and will suppose that all necessary sensor data and processing are available and functional.

4.2.2.17 Operator switches the machine to RC mode (CR220)

This function is in principle identical to CR29, and may either use the same on-screen or joystick button (the behavior is then that of a toggle between "auto" and "RC" modes) or a separate dedicated on-screen or joystick button.

4.2.2.18 The system automatically adjusts camera views. (CR223)

Based on the current function being executed and stage of the selected job, the vehicle internal software switches to the most relevant camera view. A set of alternative camera views are available for selection by the operator if needed (see CV24)

4.2.2.19 Operator triggers AutoLock function. (CR224)

A toggle button on the joystick activates or deactivates the AutoLock function. In the event where the function is active, the vehicle onboard software automatically detects sufficient proximity of the spreader twist locks to container corners in order to trigger twist lock engaging.

4.2.2.20 Operator disconnects RC console from reachstacker. (CR225)

A "DISCONNECT" push-button is available on the RC console desk, allowing the operator to disconnect from the reachstacker.

4.2.2.21 Automatic adjustment of seat height etc. based on personal settings. (CV21)

Pressing the "auto apply settings" button in the UI triggers the RC console and seat to adjust to the operator's preset settings. These include seat height, adjusted via linear actuator in the seat base, icon and camera view placement on the UI, personal KPI selection for the performance dashboard (see FV221), audio source selection and volume settings, joystick maximum vibration intensity and per-axis force and torque as well as screen brightness.

4.2.2.22 Operator selects assigned harbor terminal and assigned vehicle. (CV22, CV23)

The operator selects the desired harbor terminal to connect to through touch input directly on the on-screen menu. Alternatively, the menu could also be navigated using input from the joystick, as proposed for UC1 in functions CV12 and CV13 (see Figure 10).

4.2.2.23 Operator switches camera view. (CV24)

Similar to the harbor and vehicle selection, the operator may select between available camera views displayed as miniature views alongside the currently active camera view, directly through touch input on the touchscreen.

Alternatively (or additionally), hand tracking may allow mid-air gestures to be used to intuitively cycle through camera views, by swiping left or right above the hand tracking camera installed on the RC console.

4.2.2.24 Operator calls up personal performance dashboard or job playback (CV30, CV31)
A button in the on-screen UI allows the operator to call up the personal performance dashboard (see FV221). Similarly, a button also allows the operator to trigger the job playback function (see FV222)

4.2.3 Control functions not yet considered
The control functions implied in the current versions of the UC2 vision scenarios which have not yet been implemented either in the state of the art or in the proposals listed above are shown in Table 6 below. If these functions are retained in the final vision scenarios, concrete implementations will have to be proposed to allow their incorporation in the D4.4 demonstrators.

KEY	CONTROL FUNCTION
CR26	At workshop or parking place, the maintenance person checks the machine visually.
CR28	Operator checks the status of the machine from the PC screen and videos
CR214	Operator checks for safety before moving the spreader. (tentative: this may not require operator input)
CV25	Operator triggers vehicle function diagnostics.
CV26	Operator calls up minimap.
CV27	Operator triggers XR assistance
CV28	Operator activates width visualization function.
CV29	Operator puts the vehicle into standby

Table 6: Control functions not yet considered for UC2

4.3 Modes of information presentation (feedback)

The analysis of the scenarios presented in Section 4.1 above yields the list of individual control functions summarized in Table 14 in the appendix Section 7.4. Below, we discuss the functions already implemented in part or in full in the state of the art, followed by a description of all proposed novel implementations.

4.3.1 State of the art
Reachstackers are conventionally equipped with a cabin providing clear visibility towards the front of the vehicle (FR28, FR224), along with rear-view mirrors and a rear-facing camera displaying its feed on an in-cabin monitor (FR220, FR224, FR228, FR237). Manipulation of containers is assessed directly visually by the operator, while contact with containers, the ground or trailers and successful locking is also assessed from auditory feedback from the environment (FR225, FR226, FR227, FR229, FR234, FR235, FR241, FR244, FR245). Onboard monitoring and control units provide relevant functional, diagnostic and fault information about the vehicle to the operator via lights on the dashboard and an in-cabin display (FR29, FR210, FR212, FV25, FV28), usually over CAN (see Figure 20). Audio communication with service or harbor personnel takes place over in-cabin radio (FR23).

4.3.2 Envisioned feedback functions

4.3.2.1 Inform operator of successful log-in (FR21)
The operator is informed of a successful login (CR21) via a change in the touch panel GUI, which displays the “Waiting for job” screen, along with information on the identity of the logged in operator. Also, the “RCC connected” indicator light lights up to signal an active connection.

4.3.2.2 Inform operator of functional RC console indicator lights. (FR22)
When pressing the RC console indicator lights button (CR22), all RC console indicator lights light up momentarily, allowing the operator to assess their correct function.

4.3.2.3 Provide audio communication to service personnel. (FR23)
If the operator contacts service personnel (CR23), the integrated microphone registers and relays the operator's voice while a microphone indicator light shows that the microphone and transmission are active. Audio feedback from the service personnel is provided through the set of connected headphones.

4.3.2.4 Inform operator of successful activation of the RC console (FR24)
Successful activation of the RC console is indicated to the operator by a notification on the touch display, which displays the UI enabling connection to a reachstacker.

4.3.2.5 Inform operator of successful connection to the reach stacker (FR25)
Successful connection to a reachstacker is indicated to the operator by a notification on the touch display.

4.3.2.6 Provide Operator with machine operation view. (FR28)
Camera streams from all available cameras, including an in-cabin view, are shown on the monitors (see also Figure 32 for the current simulation implementation).

4.3.2.7 Inform operator that RS working lights are switched on (FR29)
When the reachstacker working lights are switched on, internal vehicle diagnostics verify this and the on-screen button on the RC console touch panel changes appearance to indicate this.

4.3.2.8 Inform operator of vehicle operational state and safety. (FR210, FR211)
Internal vehicle diagnostics sensors and software verify the functional state of vehicle systems. A functional state is indicated to the operator implicitly, through the absence of warning notifications on the touch-panel UI.

In the event of a critical fault, vibration notifications could be fed back through the joystick to accompany visual and auditory warnings, ensuring the operator does not manipulate the reachstacker while ignoring the warnings. For this, an identical system to that described in UC1 for functions FR11 and FR13 (see Figure 13) can be used.

4.3.2.9 Inform operator of successful engine start (FR212)
A successful engine start is detected by the vehicle internal diagnostics system and notified to the RC console. Tactile warning for a critical failure could also be provided in this case (see FR210 and FR211 above).

4.3.2.10 Provide multiple camera views of vehicle in parking area. (FR213)
Multiple cameras located outside the vehicle in the parking area can be selected for viewing on the RC console monitors (see FR220).

4.3.2.11 Inform operator of successful activation of auto mode (FR214)
Once auto mode is successfully activated, the operator sees an on-screen notification on the touch panel confirming this.

4.3.2.12 Inform operator of successful activation of RC mode (FR215)
Since activation of the RC mode likely implies the operator will handle the joystick. A failure of activation could be notified using vibrotactile warning cues in the joystick (see FR210, FR211 and FR212 above). The absence of such notification would implicitly inform the operator of RC mode activation success.

4.3.2.13 Inform operator about list of assigned orders, pending jobs, and job selection (FR216, FR217)
A job introduction screen displayed on the touch-panel provides an overview of assigned orders and pending jobs.

4.3.2.14 Inform operator of the current job details and overview. (FR218)
Selecting a job from the job introduction screen causes the touch-screen to display a detailed overview of the job in question.

4.3.2.15 *Provide operator with the layout or minimap (FR219)*

Furthermore, a minimap of the harbor terminal is displayed on a smaller secondary monitor. This minimap provides a top-down view showing the current reachstacker location as well as locations of interest (target container or truck for loading) as well as the paths available and known potential obstacles.

4.3.2.16 *Provide operator with multiple and/or selected camera views (FR220, FR224, FR239)*

The RC console's smaller monitor can display either alternative camera views or the dashboard of vehicle parameters. Multiple monitor icons or miniature camera views on the touch-screen UI allow the operator to select the relevant views for the task at hand. Video feeds can come from cameras mounted on the vehicle itself as well as stationary or mobile cameras installed in the harbor terminal.

The current demo also investigates the option of using hand tracking gesture input to cycle between camera views. When the operator uses any of the hand-tracking features, they are aware of the input the application is receiving, and how it is responding to that. A small sphere (see Figure 24) 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.

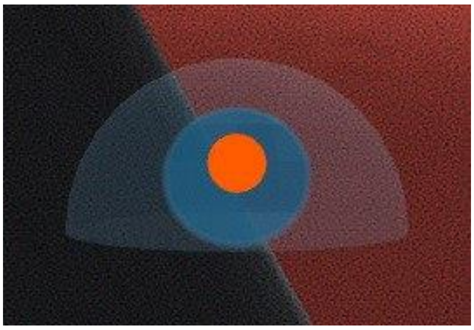

Figure 24: Feedback on hand tracking input for camera view selection in the simulation

The current camera position is implicitly indicated to the operator through the provision of the camera feed on the RC console monitor (FR239).

4.3.2.17 *Alert operator to approaching machine or object (FR221, FV210)*

Approaching machines trigger an audio buzzer alarm if the vehicle is too close. Furthermore, approaching machines are highlighted in the video streams shown to the operator. Based on the angle location, audio is rendered three-dimensionally to provide an indication of direction to the potential obstacle. If the minimap is active, an orange dot can be displayed at the location on the minimap where the other machine is operating.

4.3.2.18 *Inform operator about current set spreader size (FR223, FR238)*

The direct view to the spreader via the different camera streams available to the operator (see FR220) provides the operator with indications about the current set spreader size. Additional AR overlays on the camera views could clarify this information.

A simple vibrotactile notification in the joystick may be provided to inform the operator that the spreader has reached a preset position and/or the end-stop of its motion range.

4.3.2.19 *Highlight target and inform operator about remaining horizontal and vertical distance between twist locks and container corners (FV212, FR225)*

When targets come into view of the cameras, AR overlays are shown to highlight these targets and indicate the remaining horizontal and vertical distance between the twist locks and container corners. This distance is measured using a LIDAR installed on the boom.

In the current simulation, the container that has to be picked up is highlighted by distance lines that connect the spreader twistlocks to the container's corner castings (see Figure 25).

Figure 25: Simulated container highlight and indication of deviation between spreader and container

When approaching a container, it may also be possible to provide force feedback guidance gently pushing the joystick towards the pose required to achieve ideal placement of the spreader over the container. Depending on whether spreader and boom control is based on velocity control (state-of-the-art) or positional control, this can become more or less complex to make functional.

4.3.2.20 Inform operator that twist locks can safely be engaged/disengaged (FR226)

A light indicator on the RC console and notifications on the touch screen show the operator that the twist locks can be safely engaged based on inputs from the twist lock inductive sensors. Similarly, thanks to the reachstacker spreader force sensors, the operator can be informed that they may safely be disengaged.

Since twist locks are engaged or disengaged while the operator manipulates the joystick, a vibrotactile warning notification may also be provided to indicate that the twist locks cannot be engaged or disengaged if the operator attempts to do so in an unsuitable position.

4.3.2.21 Inform operator that twist locks have successfully been engaged/disengaged. (FR227, FR243, FR244)

The feedback scheme for this function is essentially identical to that for function FR226 above. If the twist locks are safely locked, the RC console light indicator turns green. If they are disengaged, it turns red.

Furthermore, when the container is locked or unlocked, the AR overlay content changes to suit the next action to be performed.

Finally, once the container is locked, force feedback informing of the weight of the handled container can be provided to the operator as per feedback function FV214 below, further confirming successful locking. In addition to the feedback proposed below, a transient force or torque in the direction that the joystick would move in order to lower the container could provide an intuitive feeling of the twist locks properly engaging. A transient force in the opposite direction could thus provide an intuitive feeling of the twist locks disengaging.

4.3.2.22 Inform operator that vicinity is clear for reversing. (FR228)

LIDAR, onboard cameras and radar sensors check the vehicle vicinity for potential obstacles. If any are detected, they are highlighted in the relevant camera feeds on the RC console monitor. Furthermore, an audio buzzer alarm may sound to alert the operator to a risk of collision. This audio warning can be modulated based on the distance and direction to the obstacle, in particular through the use of a 3D audio device.

4.3.2.23 Inform operator that boom and spreader are in a suitable position for driving. (FR229)

By showing the container position on the AR load chart, the augmented camera feed informs the operator of safe boom and spreader settings for driving. Additionally, boom sensors can be used to automatically detect this suitable state, allowing warning notifications to be provided to the user if the state is unsuitable (on screen notifications, audio feedback and joystick vibrations).

4.3.2.24 Inform operator about truck ID in loading order (FR230)

The truck ID in the loading order is shown on the RC console monitor.

4.3.2.25 Inform operator about ID of truck currently being loaded (FR231)

The truck ID of the truck currently being loaded is assessed using cameras and displayed to the operator on the RC console monitor.

4.3.2.26 Inform operator about ideal loading position and orientation relative to truck being loaded. (FR232)

Once the ideal loading position comes into view, the AR content on the camera streams highlights the ideal loading position and orientation relative to the truck being loaded.

4.3.2.27 Inform operator of discrepancies between container actual and ideal position for loading. (FR233)

The feedback scheme for this function is essentially a combination of that described above for functions FV212 and FR225 and that described below for functions FR241 and FV215.

4.3.2.28 Inform operator that container has been sufficiently lowered to allow release. (FR234)

When the container has been sufficiently lowered to allow release, a notification is shown on the touch display screen and/or in the AR overlay on the video feed, signaling this to the operator.

The projection of the container onto the truck's flatbed along with the overlay showing the loading position (see FV215 below) also help the operator to assess whether the container is sufficiently lowered.

Finally, force feedback can be provided when the container touches the ground, based on collision detection through microphones in the spreader or measurements from the spreader twist lock force sensors. This force feedback would ideally take the form of a virtual end-stop applied to the joystick motions along the relevant axes, informing the operator that the container is in contact with the ground. Alternatively, vibrotactile feedback of collision with the ground may also be used to provide this information to the operator through the joystick handle.

4.3.2.29 Inform operator of the presence of persons in the vicinity of the vehicle (FR236)

LIDAR, radar and cameras on the vehicle scan the surroundings, allowing the onboard software to detect persons in the vicinity of the vehicle. Detected persons are highlighted in the camera feed shown to the operator.

Audio feedback similar to that discussed above for function FR221 above may also be used to alert the operator to the presence of persons in the vicinity of the vehicle. The end of this audio feedback provides implicit confirmation to the operator that persons have left the vicinity of the vehicle.

4.3.2.30 Provide operator with clear vision and earshot of the vehicle vicinity (FR237)

The use of vibrotactile notifications rather than audio notifications in the relevant functions (CV21, FR210, FR211, FR215, FR223, FR226, FR229, FR234, FR238, FR240, FR248) is an approach that reduces audio clutter and thus indirectly contributes to providing a better earshot to the vicinity for the operator.

4.3.2.31 Inform operator that ideal or desired driver cab position has been reached (FR240)

An inductive sensor measures the current driver cab position. If the operator reaches the ideal calculated or desired driver cab position, a notification is provided on the RC console screen.

If the driver cab position is being set using the joystick, a simple vibrotactile notification may be provided to alert the operator that either the desired position has been reached or the end stop of the driver cab motion has been reached.

4.3.2.32 Inform operator that spreader has reached suitable position for picking / lowering container (FR241)

The operator uses the available camera views, augmented with various AR overlays to assess the current position of the spreader (and possibly container) with respect to the target position.

In the current demo, AR content shows both the planar and vertical alignment of the spreader relative to the target container. Both the distance lines and the symbols are color coded to be orange, yellow, and green based on the distance they represent. Arrows show planar alignment, while circles show vertical proximity (see Figure 26).

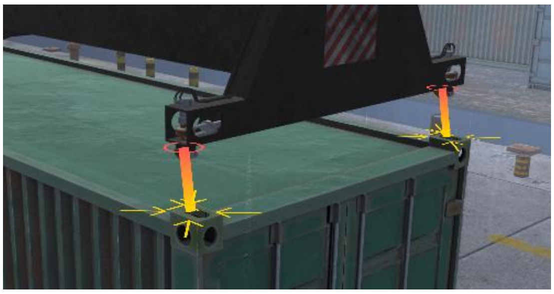

Figure 26: AR overlay showing planar and vertical alignment of spreader and container

Another option when handling a container would be to display the current container location on an AR load chart, simplifying the assessment of container position relative to a placing target.

"Soft" guidance force feedback similar to that discussed in UC1 (see Section 3.3.2) could also be activated either automatically during spreader maneuvering in proximity of a container or on demand by the operator (through e.g., a button press on the joystick) so as to exert a force proportional to the remaining distance in the direction of possible misalignments between spreader and container. The absence of such a force would implicitly indicate to the operator that the suitable position for picking up the container has been reached.

4.3.2.33 Inform operator that spreader has been sufficiently lowered to allow AutoLock function to run (FR242)

Force feedback may be provided when the spreader comes into contact with the container, using the same approach as that described for when the handled container touches the ground in function FR234 above.

In the event where the operator attempts to trigger the AutoLock function while this is not possible, the system may detect the unsuccessful attempt using the twist lock sensors and internal diagnostics data and notify the operator of AutoLock failure through vibrotactile feedback in the joystick handle.

4.3.2.34 Inform operator that the boom and spreader are in a suitable position for transport. (FR245)

The feedback scheme for this function is essentially identical to that described for function FR241 above.

4.3.2.35 Inform operator that RC console is disconnected from reachstacker (FR248)

When the operator disconnects from the reachstacker by pressing the "DISCONNECT" button on the RC console (CR225), the light on the disconnect push-button switches on. A notification is also displayed on the RC console touch-screen, confirming disconnection. Implicitly feedback is given through the fact that force and vibration feedback to the joystick stop and the monitor shows that the reachstacker movements have stopped.

4.3.2.36 Inform operator that destination has been reached (FR249)

When a destination is reached, the AR overlay content can also change to fit the next action in line. In this way, the operator is implicitly notified that the destination has been reached.

Since reaching a destination likely follows automatic or manual driving of the machine, there is no guarantee that the operator has their hands on the joystick. Therefore, tactile notifications do not appear sensible for this function.

4.3.2.37 Inform operator about current driving functions being executed (FV28)

Microphones mounted on the vehicle can provide real-time audio feedback to the operator through the headphones connected to the RC console, allowing them to assess which driving function is currently being executed.

4.3.2.38 Inform operator about relative position of objects and vehicles in the environment (FV29).

This function is accomplished through the combination of functions FR221, FV210 and the provision of augmented camera feeds showing the vehicle vicinity to the operator (FR220).

4.3.2.39 Highlight target container or truck in augmented camera view. (FV212)

Based on GPS vehicle positional data and image processing on the camera streams, the target container or truck can be highlighted in the camera views as soon as they come into view. This highlight may be implicit through the execution of functions FV215 and FR225, or may imply additional visual feedback, e.g. projecting a frame around the truck or container.

4.3.2.40 Inform operator about container weight and/or center of mass. (FV214)

After a container has been locked and raised, its weight and center of mass are determined using the twist lock force sensors and shown on the AR camera stream. The operator can shift the spreader (and container) on the left and on the right to align the container's center of mass with that of the reachstacker. To raise and lower the container, the operator can check the AR load chart to be sure that the container is in a safe position and there is no risk of it tipping over during transport.

Figure 27: Simulated AR visualization of container mass and centre of mass

Force feedback is an intuitive modality to inform operators of the handled container mass, however generating a force or torque (depending on the mapping of joystick to spreader motions) along the joystick axis used to raise or lower the container poses the issue of forcing the operator to "fight" the joystick in order to keep the container at a given height, which could potentially be cumbersome and a safety hazard. Rather, it seems more appropriate to indicate handled container mass by applying a temporary damping to joystick motions controlling the spreader, which is proportional to the mass of the handled container as measured by the twist lock sensors.

An alternative would be to provide a pushbutton on the joystick allowing the operator to switch between a "control" and a "feedback" mode on the joystick. In the "control" mode, the joystick would operate the boom and spreader as per the chosen control scheme. In "feedback" mode, the joystick would be decoupled from the boom and spreader and instead apply forces and torques to the operator's hand proportional to the forces and torques exerted by the container on the spreader. This could allow the operator to sense any imbalance and to correct it by switching back and forth between modes.

4.3.2.41 *Project the container limits or ideal loading position on the ground (FV215)*
The container's target location is highlighted with AR in the camera views available to the operator (see e.g., Figure 28). When the container is aligned with the ideal position, the highlights can change color to green to indicate this. Furthermore, a light indicator on the RC console may also turn green to signal reaching the ideal position.

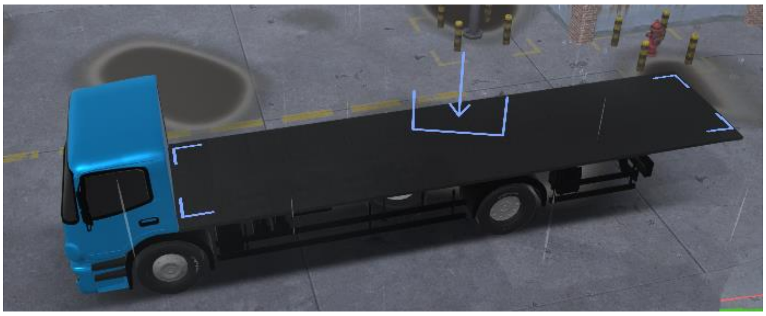

Figure 28: Simulated AR highlight of target container loading position

4.3.2.42 *Inform operator of relative width of vehicle and container to free space in which the vehicle navigates. (FV218)*
The relative width of the vehicle and container to free space in which the vehicle navigates is shown to the operator as an AR overlay on the camera view.

The vibrotactile actuator in the joystick handle could provide warnings of imminent collisions as sensed using e.g., LiDAR or computer vision algorithms applied to the camera streams. If distance information is available for the imminent collision, vibration pulse trains of increasing frequency could provide an intuitive sense of the remaining distance before collision as well as of the efficacy of corrective measures undertaken by the operator. This modality provides the advantage of highly salient feedback, but should probably be considered as an addition to a modality capable of providing clearer spatial information (e.g., visual feedback).

4.3.2.43 *Inform operator of optimal path to follow in tight corridors of the port. (FV219)*
The optimal path to follow in tight corridors of the port is shown to the operator as an AR overlay on the camera view.

4.3.2.44 *Inform operator that vehicle has successfully been put into standby. (FV220)*
When the vehicle is successfully put into standby (CV29), this is signaled to the operator through an on-screen notification. Furthermore, control actions on the reachstacker have no effect before switching out of standby, implicitly informing the operator of the vehicle state.

4.3.2.45 *Provide operator with a personal performance dashboard (FV221)*
When the operator calls up the personal performance dashboard UI (CV30), they are shown a screen summarizing the number of containers delivered today, distance driven, average time per pick-up and placement process. Furthermore, a comparison to previous workdays is provided.

4.3.2.46 *Provide operator with a fast-forward playback of the day's driving path (FV222)*
When the playback function is activated (CV31), the RC console screen plays back a fast-forward of the day's driving path.

4.3.2.47 *Inform operator of successful logout of the RC desk. (FV223)*
The operator is notified of successful logout from the RC desk through the on-screen display of the touch panel returning to the login screen.

4.3.3 Feedback functions not yet considered
The feedback functions implied in the current versions of the UC2 vision scenarios which have not yet been implemented either in the state of the art or in the proposals listed above are shown in Table 7 below. If

these functions are retained in the final vision scenarios, concrete implementations will have to be proposed to allow their incorporation in the D4.4 demonstrators.

KEY	FEEDBACK FUNCTION
FR26	Inform operator of preset vehicle settings associated with recognized operator ID
FR27	Inform operator that personalized vehicle settings have been successfully applied.
FR222	Inform operator about safe space available for extending spreader
FR246	Inform operator that the job is complete
FR247	Inform operator that RS is safely stopped and ready for disconnect.
FV21	Inform operator about assigned harbor terminal.
FV22	Inform operator about selected harbor terminal
FV23	Inform operator about assigned vehicle.
FV24	Inform operator about selected vehicle.
FV26	Inform operator about ideal route to target location.
FV27	Inform operator about distance to the target location.
FV210	Inform operator about distance to objects and vehicles in the environment.
FV211	Inform operator about predicted trajectory of vehicles in the environment.
FV213	Provide operator with AR overlays on video during manual remote driving
FV216	Display persons in the vicinity on the minimap
FV217	Highlight persons in the vicinity in the camera views

Table 7: Feedback functions implied in the UC2 scenarios which have no proposed implementation

4.4 UC2 Demo specification

The playable demonstration for the reachstacker use-case will be developed under the heading of VTT, who are in the process of building a virtual environment capable of hosting both physical and simulated UI elements showcasing the control and feedback functions previously discussed.

Once again, we begin by presenting the virtual environment, vehicle, and giving an overview of the simulated sensor data that is available. Physical UI elements required for interacting with this demo are briefly discussed, providing relationships with work from deliverable D5.5. We follow this with a discussion of simulated UI elements necessary to completely cover the spectrum of control and feedback functions we wish to evaluate. Finally, we recap the sequence of actions and events from the deliverable D3.2 scenarios that we plan to use as the simulation scenario.

4.4.1 Virtual environment, vehicle simulation and sensor data simulation

The testing environment tries to resemble as much as possible a real working environment. Since reach stackers are used mostly in logistic hubs, a harbor asset was chosen (see Figure 29).

Figure 29: Simulated harbor for the UC2 demonstrator

The task focuses on the control of boom and spreader (see Figure 30). The boom can be rotated upward or downward, and its telescopic arm can be extended or retracted. The spreader can be shifted to the left or right, and it can also be rotated clockwise and counterclockwise. Input mapping has been kept the same as the real reachstacker's joystick (see Section 4.2.1), with axis values to control the boom and buttons to control the spreader.

Figure 30: Simulated reachstacker boom and spreader DoF

Wind strength and direction are only shown in the UI with a compass symbol that rotates to adjust to the direction the user is facing. Both direction and strength are constant, and they do not affect the simulation. They are meant to give an idea of what the user would see in a real scenario.

Data acquisition by the vehicle's virtual sensors is considered perfect, i.e. there is no measurement noise or uncertainty creating offsets between the "true" simulated data and the "sensed" simulated data. The simulated vehicle itself contains a virtual throttle sensor and IMU feeding back acceleration and orientation information. These sensors also behave in an ideal fashion. The simulated boom and spreader feature a virtual LIDAR sensor (see Figure 31). The LIDAR simulation consists in casting about 10000 rays every 0.3s from a specified position in the bottom part of the boom (where the real LIDAR could be placed), towards the front of the vehicle. Because of the resource-intensive task of ray casting in Unity, rays were shot precisely in the direction of one of the container's corners, with a total angle of 30° both for azimuth and zenith. If the user wants to visualize another angle, they can press the left and right arrow keys on the keyboard, so that the virtual camera is moved to the new corner, and the raycast is rotated towards the new corner's position. In a real environment, a normal LIDAR could possibly be capable of shooting rays on the whole container all the time, without the need to rotate it.

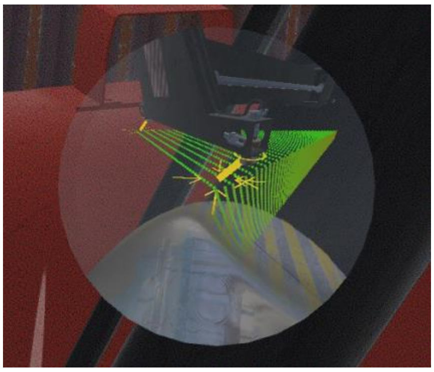

Figure 31: Simulated LIDAR

The spreader twistlocks contain virtual weight sensors which currently return the scripted weight and center of mass position of handled containers when the twist locks are engaged, once again behaving as ideal sensors. This allows the simulation to remain free of issues that would likely be introduced by a proper physics simulation, while providing essentially the same functionality when it comes to evaluating interactions.

Finally, the demo presents a set of four 360° cameras for the user to monitor, namely one inside the operator's cabin, one on the top of the spreader, one in the back of the vehicle for safety purposes, and a "drone view" camera (see Figure 32). The latter camera is more of an experimental one, and for the sake of feasibility can also represent a camera out of a light pole or in any other place of the logistic hub that provides a useful point of view of the reachstacker's task.

Figure 32: Available simulated camera views in the UC2 simulator

4.4.2 Physical UI elements

The simulation display consists of three wall-sized screens, placed with an angle of 120° between each other. The total screen resolution available is 5760x1200 pixels. As input devices, the demo currently makes use of a Logitech Extreme 3D joystick for controlling the reachstacker's boom and spreader, and an Ultraleap Stereo IR 170 hand-tracking device for controlling the camera views and their position on the screen. A keyboard is also used for handling simulation aspects (such as changing the weather from rain to snow, etc.), and also for proving specific commands that were not bound to any of the other peripherals (such as disabling one or both of the AR load charts). The demo intentionally includes a high number of features available to the user, in order to understand which ones are felt to be the most useful and which ones are not really needed. Finally, a Haption Virtuose 6D haptic device is used as a stand-in for the future haptic device designed within the THEIA^{XR} project (see deliverable D5.5), to test haptic feedback when controlling the boom and spreader of the reachstacker.

This required setup is likely to evolve as the prototype implementation of the different control and feedback functions progresses. The definitive specification for the UC2 demo UI elements will be provided in the final version of this deliverable.

4.4.3 Simulated UI elements

The full size of the screens is used to show real-time camera footage from several 360° cameras placed both on the vehicle and on key location of the logistic hub. On the UI overlay, the user can see the wind strength and direction, as well as temperature, humidity, and the vehicle's throttle projected on a virtual head-up display (HUD). On the wall-sized display, the user is also shown a simulated "LiDAR view", that brings together a virtual representation of the reachstacker'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 (see Figure 31).

4.4.4 Envisioned scenario tasks

The definitive sequence of scenario tasks will only be agreed upon once work from deliverable D3.2 has completed and both the scenarios and lists of component control and feedback functions reach their final state. However, VTT have begun prototyping a certain number of scenario events and functions in the context of user testing for the co-design process, which will likely form the basis of the final demonstrator.

Currently, during VTT's user tests and demos, users are asked to complete a task divided into the scenario steps described in Table 8 below. The task consists in picking up a container from the ground and placing it down on a truck's flatbed at a later time. Users are not asked to drive the vehicle, because of the assumption that the reachstackers will be able to reach their target location autonomously (CR210, CR213). The task consists of the following steps:

STEP	DESCRIPTION CONTROL FUNCTIONS	TYPE	OBJECTIVE SHOWN IN UI FEEDBACK FUNCTIONS
1	Application starts	Scripted event	
2	Users gets used to the controls and raises the boom (CR215, CR216, CV24)	User task	Press "F1" to display the controls layout. Adjust the cameras and raise the boom to the travel position. Press "Enter" to proceed. (FR28, FR210, FR213, FR239)
3	The reach stacker moves towards the shipping area (CR213)	Scripted event	Keep an eye for obstacles! Press "Space" for emergency stop, press "Backspace" to resume movement. (FR214, FR220, FR221)
4	User moves the cabin forward (CR221)	User task	Move the cabin forward for better visibility. Press "Enter" to proceed. (FR240)
5	The harbor crane puts a container on the ground and the reach stacker drives next to it (CR222)	Scripted event	Preparing the container, please wait... (FV212)
6	AR features activate (container load chart) (CV27)	Scripted event	
7	The user controls the boom and spreader to pick up the container (CR214, CR215, CR216, CR217)	User task	Position the boom above the container. Align spreader arms with the container and lower the boom. Press "Enter" to engage twist locks. (FR223, FR224, FR225, FR226, FR227, FR241, FR244)
8	The user raises the container and adjusts the center of mass. (CR215, CR216)	User task	Raise the container and shift it to eliminate the center of mass offset. Move the container to travel position according to the load chart. Press "Enter" to proceed. (FR229, FR245, FV214, FV215)
9	A truck arrives to the harbor and the reach stacker drives next to it (CR222)	Scripted event	(FR232)

10	The user places the container on the truck's flatbed (CR215, CR216, CR217)	User task	Position the container above the target location and lower the boom. Press "Enter" to disengage the twist locks. (FR233, FR234, FR241, FV215)
11	The user retracts the spreader from the container to let the truck leave (CR215, CR216)	User task	Raise the boom above the container and retract it to the travel position. Press "Enter" to proceed. (FR235, FR238)
12	The truck leaves and the reach stacker returns to the shipping area (CR29, CR213)	Scripted event	*The application starts back the loop from point 5.* (FR246)

Table 8: Currently implemented scenario tasks and functions in the UC2 demo

5 Use-case 3: Excavator

5.1 Scenario analysis

Task T3.2 provided a set of two scenarios for the excavator use-case: a “*realistic*” scenario focused on control and feedback functions implementable in-vehicle in the short term, and a “*visionary*” scenario focused on a more long-term perspective of a potentially teleoperated vehicle.

The analysis of component tasks for each is presented in the Table 9 and Table 10 below.

Scenario section	Component task
Jonas starts the engine of the excavator and checks if all the systems are working. As the engine roars, several small screens and light bars around the entire front window light up and a bright “Theia” logo appears projected on the ground in front of the excavator.	**Control:** Operator starts the engine. **Feedback:** Inform operator of the engine status. **Control:** Operator calls up systems diagnostics test. **Feedback:** Inform operator of system functional state. **Feedback:** Inform operator of functional state of the XR assistance
Jonas moves the excavator towards the area that his supervisor pointed out to him.	**Control:** Operator drives the excavator to a defined location.
As he approaches the marked spot on the ground, the assistance system picks up on the markings and a bright laser rectangle lights up around the indicated area that Jonas can adjust on one of the screens.	**Control:** Operator orients the excavator with respect to a defined target location. **Feedback:** Inform operator of reaching a desired vehicle position/orientation.
Length and width of the pit have already been correctly registered by the system, so now Jonas only needs to set the depth of the excavation pit.	**Control:** Operator calls up a visualization of the planned excavation on screen. **Feedback:** Inform operator of intended excavation geometry.
On one of the screens an animation shows up, indicating that the calibration of the movable parts has already been completed in the background via a laser measuring the exact position of the ground and the bucket.	**Control:** Operator adjusts the dimensions of the planned pit. **Feedback:** Inform operator of proper dimensional settings with respect to prior excavation plan. **Feedback:** Inform operator of successful calibration of excavator moving parts.
Jonas decides to start with the top right edge of the pit. As he scoops up a bucket full of soil, the light bars on the left and right side of the front window display a familiar color gradient, indicating how close the tip of the bucket gets to the target depth.	**Control:** Operator digs into soil. **Feedback:** Inform operator of distance to the target excavation depth. **Control:** Operator scoops up load of soil **Feedback:** Inform operator of bucket fill level.
While the machine swings to the left, an environment monitoring screen near the front window displays a panoramic view of the surrounding area.	**Control:** Operator swings and moves bucket **Feedback:** Provide operator with an unobstructed view of the surroundings.
As Jonas keeps digging and unloading his buckets to the left, suddenly he hears a noise from the right cabin speakers and the light bar to the right of the front window flashes in red.	**Control:** Operator unloads to an intended location on the side. **Control:** Operator empties bucket.
Alarmed, Jonas checks the screen, which shows that one of his co-workers is passing by close to the vehicle, seemingly in a rush and unaware of the excavation in progress right next to him.	**Control:** Operator interacts with warning system **Feedback:** Inform operator of an immediate danger in the vicinity.

With the touch of a button, Jonas activates the environment warning system and a moving orange laser pattern is being projected on the ground to the right of the vehicle, catching his co-worker's attention, who now hurries out of the Slewing radius.	**Control:** Operator activates the environment warning system. **Feedback:** Inform operator of successful activation of environment warning system. **Feedback:** Inform persons around of excavation in progress. **Feedback:** Inform persons around of exact limits of danger zone (swiveling radius).
Later, Jonas' supervisor returns, approaching the vehicle from the left and popping up in the environment monitoring screen. Jonas powers the vehicle down and leans out of the door. He is informed that he needs to dig a narrow straight trench from the completed excavation pit to another cable access point in the ground twelve meters away.	**Control:** Operator powers down the vehicle temporarily. **Feedback:** Inform operator of the presence of a person near the vehicle. **Feedback:** Inform operator that the vehicle is powered down.
As soon as the first pit is finished, Jonas turns the excavator around and aligns it centered and parallel to the direction of the planned trench. He sets up the dimensions of the trench adjacent to the original pit in the onboard system and the planned trench is promptly projected onto the ground as well.	**Control:** Operator rotates the excavator. **Feedback**: Inform operator that the excavator is aligned with intended digging direction. **Feedback:** Inform operator about successful activation of trench assistance system. **Control:** Operator teaches the outline of the trench by moving the bucket to the outline positions **Control:** Operator enters / adjusts the dimensions of the trench
As Jonas scoops up the first layer of soil, he activates the trench assistance system and immediately sees additional thin bright lines projected on the ground, around a meter to the left and to the right of the edges of the trench, indicating the zone between trench and unloading area that should be left free for the vehicle tracks to drive on. As soon as the trench has reached the desired depth in Jonas' comfortable working distance, he swings the upper carriage around by 180 degrees to the left, reverses the vehicle by a few meters, then swings around to the left again to continue digging on the next part of the trench.	**Control:** Operator works on trench and repositions excavator **Feedback:** Inform operator about the location of the edges of the trench. **Feedback:** Inform operator about ideal unloading area. **Feedback:** Inform operator about the zone to be left free for vehicle tracks to drive on. **Feedback:** Inform operator about reaching desired excavation depth. **Control:** Operator triggers XR visualization of the trench. **Control:** Operator rotates the excavator. **Control:** Operator reverses the vehicle by a defined distance.
As time goes on, Jonas tries to scoop up increasingly heavier amounts of soil in the bucket to complete the trench faster. At one point the horizontal light bar on the bottom of the front window flashes yellow and a message appears on one of the cabin monitors, indicating that the load in the bucket is approaching a critical weight and offering Jonas to activate machine efficiency monitoring.	**Control:** Operator scoops up (heavy) load of soil / Operator increases the quantity of soil being scooped up. **Feedback:** Inform operator about the quantity of scooped soil. **Feedback:** Inform operator that the bucket load is approaching critical weight.
Jonas accepts and keeps an eye on the light bar on the bottom of the front window as he continues digging, slowly getting an intuitive feel for the ideal load in the bucket.	**Control:** Operator activates machine efficiency monitoring. **Feedback:** Inform operator of the critical load. Inform operator of current machine efficiency.

Jonas places the bucket on the ground, moving boom, arm, and bucket away so that the hydraulic cylinders are as little extended as possible. He releases the control lever to lock all moving parts, lowers the gas, powers down the engine, and exits the cabin. Before he can power down the machine, he waits another minute until the AdBlue has been pumped out of the engine and the machine gives a high-pitched signal	**Control:** Operator retracts hydraulic cylinders. **Feedback:** Inform operator of successful retraction of all hydraulic cylinders. **Control:** Operator places bucket on the ground. **Feedback:** Inform operator of successful safe placement of bucket on the ground. **Control:** Operator locks all moving parts. **Feedback:** Inform operator that all moving parts are locked. **Control:** Operator powers down the engine. **Feedback:** Inform operator that the engine is off. **Control:** Operator powers down the XR assistance. **Feedback:** Inform operator of XR assistance system shutdown.

Table 9: Scenario analysis for the UC3 "realistic" scenario

Similar to UC1, there is almost total overlap between the component tasks in both scenarios, with the exception of an additional control task related to starting XR assistance features, see Table 10 below which highlights the significant changes that appear in the "*visionary*" scenario.

Scenario section	Component task
As the engine roars, he puts on the lightweight XR headset stored in an overhead compartment of the cabin and sees a bright "Theia" logo appear in the center of his field of vision on top of the clear visuals of the cabin around him.	**Control:** Operator starts up the XR assistance
As Jonas scoops up the first layer of soil, he activates the trench assistance system and immediately sees additional thin bright lines projected on the ground, …	**Control:** Operator activates the trench assistance system

Table 10: Scenario analysis for the UC3 "visionary" scenario

5.2 Availability of control functions (input)

The analysis of the vision scenarios presented in Section 5.1 above yields the list of individual control functions in Table 15 in the appendix Section 7.5 below.

5.2.1 State of the art

Conventional excavators use a combination of joysticks, pedals, a steering wheel, keypads and other physical control elements to control the several functions of the machine. Keypads, or small touch displays in more modern vehicles, are used to set up the machine: (starting (CR31, CR326), control of power distribution, control of the support beams, switching modes etc.).

If the machine is set up for driving, pedals and a steering wheel are used to control direction and speed (CR33, CR34, CR318, CR320). Additionally, a parking brake and slewing brake are used to stop the tracks and carriage rotation (CR325).

Excavators can be used with a variety of tools (e.g., buckets of different shapes and sizes, grippers, hydraulic hammers, shaker, and many more) that require unique control features. As the analog buttons of excavators must cover all these functionalities, a lot of space is used to accommodate them, usually in the right armrest.

In work mode, two joysticks are used to control the four degrees of freedom of the tool (tool angle, arm angle, boom angle, and carriage rotation) as per the control pattern in use on the vehicle (see Figure 33). Joystick rotation angles map to rotation velocity around the controlled DoF.

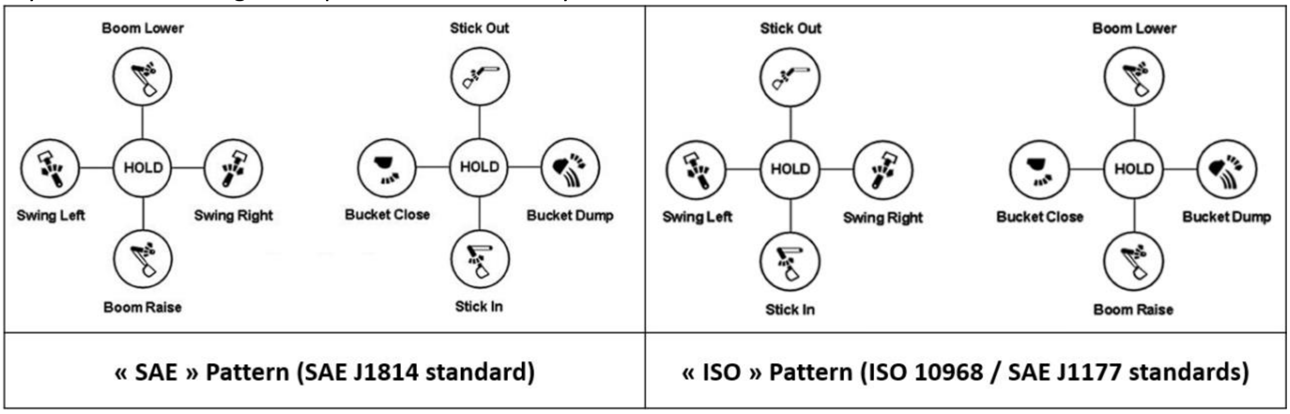

Figure 33: Two most common excavator joystick control patterns[2]

Some excavators have even more degrees of movement that are often mapped on thumb-joysticks or switches mounted on the joysticks. This tool operation covers control functions CR37, CR38, CR39, CR310, CR311, CR315, CR318, CR321, CR323 and CR324.

Regarding the tool control, excavators have safety features that are implemented to prevent mishandling. The most prominent function, is a lever, mounted on the left armrest, that have to be brought into working position, which connects the joysticks to the control circuit, to make them effective (CR325).

5.2.2 Envisioned control functions

5.2.2.1 Operator calls up systems diagnostics test. (CR32)

Within the cabin, a Graphical User Interface (GUI) is deployed on a tablet, with which the operator can interact by touching the display. As soon as the machine is started, it shows automatically the system diagnostics test and informs the human operator if there are any problems. This information is directly depicted on the screen.

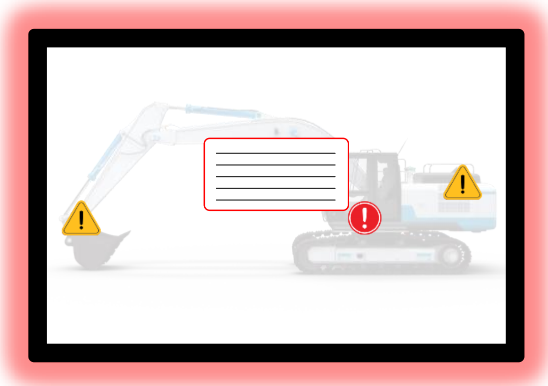

Figure 34: Display highlighting system diagnostics

The display receives direct information from the machinery, making it able to directly highlight the system diagnostics. It receives the current information about all vital systems of the machine. If there are some critical errors that need to be handled before operation, they are depicted on the screen, directly informing the operator where the error is. By selecting the error-icon, information pops up describing the situation. Additional information or notification provided to the operator of the current states of the machine could be

[2] Figure adapted from Proctor et al., 2022 [2]

that the configuration of the GUI is highlighted as a warning (e.g., red for error, yellow for warning and green for correct operation). Figure 34 highlights these potential features.

5.2.2.2 Operator calls up a visualization of the planned excavation on screen and adjusts its dimensions. (CR35, CR36)

The operator can call up visualization of planned excavations on the touch-screen by selecting an excavation model from the local file storage. This model can be used to update the digital terrain model so as to obtain a preview of the future layout and make adjustments, or can be displayed as an overlay on top of the scanned environment (reconstructed from LIDAR) for the operator to assess correctness of the plan or vehicle placement and alignment. The planned excavation is displayed on the GUI on the tablet, informing the human operator clearly where the excavation has to take place and how, based on the available information (machine settings, terrain model, etc.).

By entering key excavation dimensions or manipulating key-points in the visualization of the excavation, the operator can adjust the dimensions of the planned pit.

5.2.2.3 Operator activates the environment warning system. (CR312, CR313)

The interaction currently described in the vision scenario may be somewhat overly futuristic. It could be more sensible to envision an interaction where the operator activates the environment warning system once a person is noticed in the danger zone. Following this, machine motions are automatically stopped to avoid collisions and a light indicator shows the outside person that they have been recognized (see FR315).

The human operator activates the environment warning system on the tablet, by pressing the specific button on the screen, which activates it. Potentially, the GUI is displayed differently (e.g., different layouting, color, etc.) to inform that the environment warning system has been activated.

5.2.2.4 Operator powers down the vehicle temporarily. (CR314)

The operator disengages the safety lever and uses the engine speed buttons to stop all motions. The engine speed could also go down automatically after 30 seconds of idling.

5.2.2.5 Operator activates the trench assistance system. (CV32)

The human operator activates the trench assistance system on the tablet, by pressing the specific button on the screen, which activates it. Potentially, the GUI is displayed differently (e.g., different layout, color, etc.) to inform that the trench assistance system has been activated.

5.2.2.6 Operator teaches the outline of the trench by moving the bucket to the outline positions (CR316)

The operator moves the bucket (as per the state-of-the-art described in Section 5.2.1), which is tracked and registered with respect to the digital terrain model using a combination of GNSS for vehicle localization and IMUs mounted on the vehicle links, allowing an estimation of the bucket location through forward kinematics. The operator uses dedicated buttons on the joystick to identify, adjust or remove key-points defining the excavation outline. Furthermore, key features in the surroundings (e.g. curbs, marker posts) could be detected by the CV system and displayed on the digital model shown on the touch-screen. The operator could then also select these features to add them as key-points in the defined excavation outline.

5.2.2.7 Operator adjusts the dimensions and triggers the XR visualization of the trench. (CR317, CR319)

An on-screen dialog prompts the operator to enter the desired depth of the trench, its inclination angle and side slopes. This updates a virtual model of the trench registered to the vehicle’s location, allowing a preview of the result to be displayed on the XR display on the touchscreen (see Figure 35).

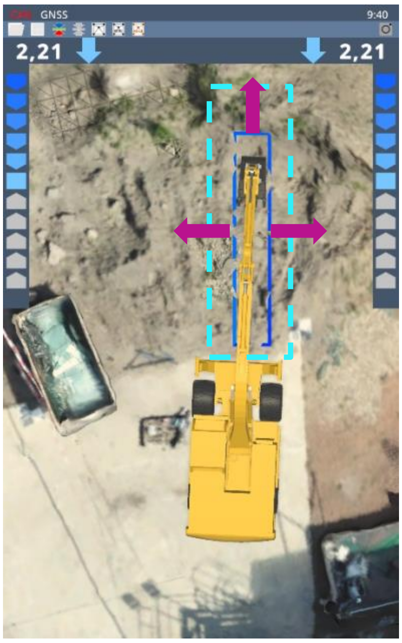

Figure 35 Visualization of the trench model (blue outline), projected on the terrain model

The human operator can also explicitly activate the XR visualization of the trench on the tablet, by pressing the specific button on the screen, which activates it. The GUI will go into a different mode, highlighting the XR visualization.

5.2.2.8 Operator activates machine efficiency monitoring. (CR322)

Implementing functional and useful machine efficiency monitoring is a non-trivial research task which is out of scope of the THEIA^{XR} project, therefore only a mock-up of a hypothetical interaction with a machine efficiency monitoring system could be proposed in the demonstrator, using a "wizard-of-oz" approach. For this, the human operator would activate the machine efficiency monitoring system on the tablet touch-screen, by pressing the correct button, activating the function. Potentially, the GUI is displayed differently (e.g., different layouts, colors, etc.) to inform that the machine efficiency monitoring system has been activated.

5.2.2.9 Operator starts up or powers down the XR assistance. (CV31, CR327)

Key switches available to the operator allow them to start up and power down the XR assistance. Alternatively, buttons on the tablet touchscreen could fulfil the same functions. Pressing the specific button on the screen would power down the assistance. Potentially, the GUI is displayed differently (e.g., different layouting, color, etc.) to inform that the machine efficiency monitoring system has been de-activated.

5.3 Modes of information presentation (feedback)

The analysis of the vison scenarios presented in Section 5.1 above yields the list of individual feedback functions in Table 16 in the appendix Section 7.6 below.

5.3.1 State of the art

The use of small displays is common in excavators. In basic configurations, these are used to show camera streams for environment surveillance (FR310) or visualize machine and process data (FR31, FR32, FR316, FR326). With the age of advanced digital modelling and connectivity, bigger touch displays were introduced in excavators. They are used to display virtual models of the machine, the construction site (FR35) and the environment and provide map, communication, maintenance, and task planning functions. Successful machine operation is mainly assessed through direct visual feedback from the concerned machine parts (FR316, FR327, FR328, FR329, FR330).

5.3.2 Envisioned feedback functions

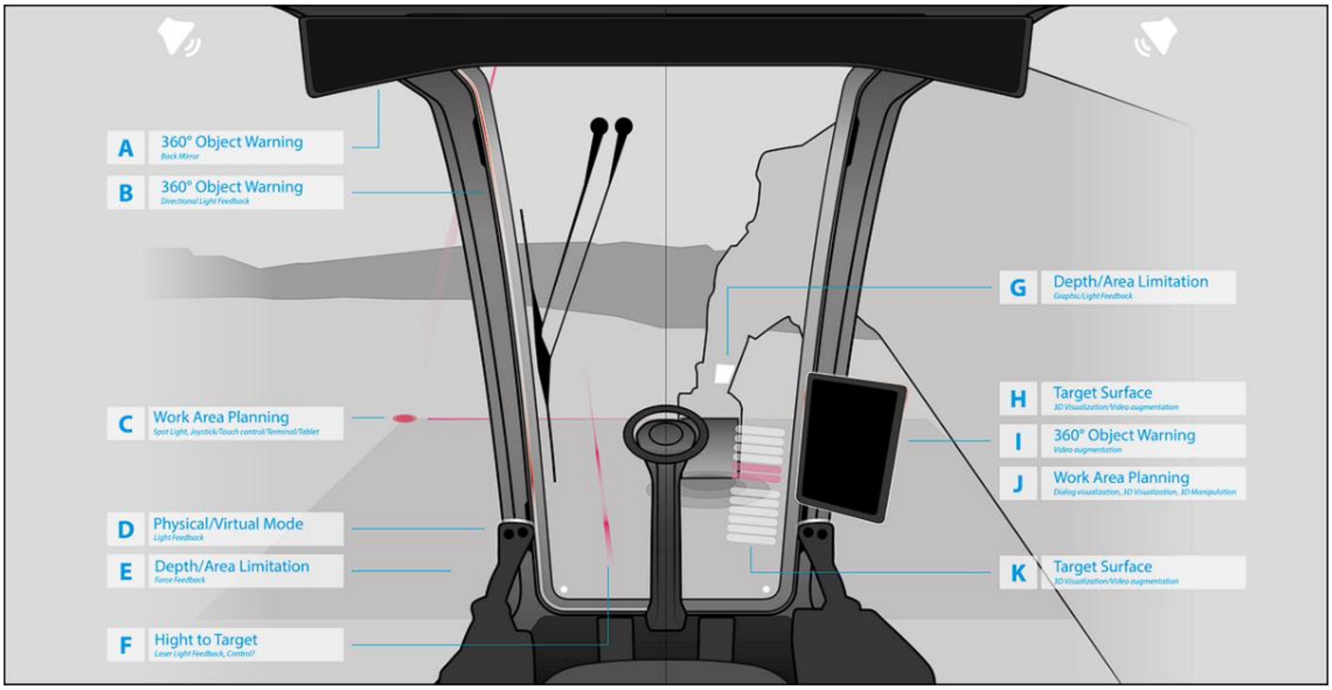

Figure 36: Exemplary visualization of feedback function concepts

5.3.2.1 Inform operator of system functional state. (FR31, FR32)

The system functional state and engine state can be displayed to the operator in the form of a basic dashboard resembling that found in any vehicle on the touch-screen GUI. This would provide information obtained from the engine electronic control unit (ECU) obtained via CAN-bus from the engine, including motor active or idle state, the power level, oil temperature as well as fault and diagnostic messages.
Furthermore, it would provide information on the state of additional systems such as the collision avoidance system, 3D machine control system and vehicle cameras.

This information should be displayed in such a way as to not disturb the operator in their tasks. If something critical occurs, the tablet changes (e.g., sound, blinking, layout, color) and informs the operator.

5.3.2.2 Inform operator of functional state of the XR assistance. (FR33)

The functional state of the XR assistance system, as assessed by the IPC, is indicated through a notification on the touch-screen GUI. Furthermore, the operator is implicitly informed about the state of the XR system through the availability of XR assistance features (or lack thereof).
This information is displayed in such a way that it is not disturbing the operator in its tasks. If a critical error occurs, the tablet changes (e.g., sound, blinking, layout, color) and informs the operator.

5.3.2.3 Inform operator of reaching a desired vehicle position and orientation. (FR34)

The touch-screen display provides a 3D visualization of the machine and environment, in which a previously defined target location and orientation can easily be added. The vehicle is localized using GNSS and the virtual model of the vehicle is shown in real time in the 3D environment visualization. Reaching a target is therefore directly visible on the touch-screen.
Additionally, the LED-matrix display on the excavator arm and in-cabin HUD (K in Figure 36) both provide information allowing for accurate assessment of deviations from a target height.
The GUI could further inform the operator that the specific position and orientation have been reached by adding highlights on the display when this is the case.

5.3.2.4 Inform operator of intended excavation geometry (FR35)

Once the operator has loaded the 3D model of the intended excavation (e.g., pit or trench), it immediately shows up in the 3D environment representation shown on the touch-screen, in the form of a visualization mapped on the digital representation of the surrounding topology (see Figure 37). This confirms the currently set excavation geometry to the operator, allowing them to perform a sanity check and possible required adjustments.

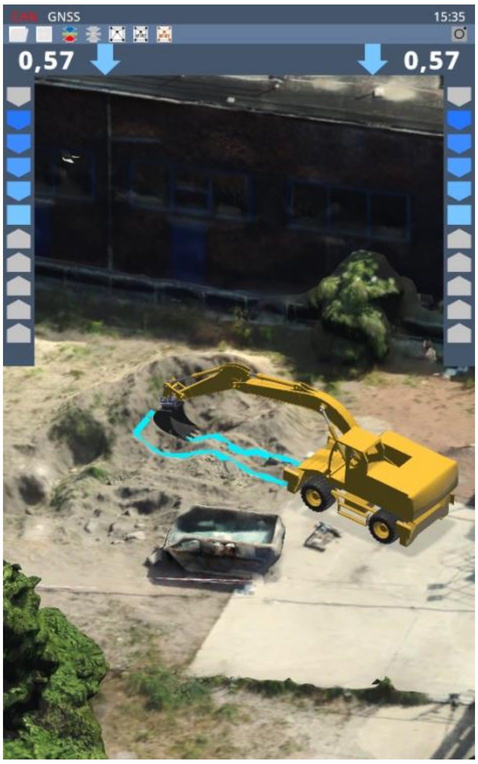

Figure 37: Visualization of the target pit/trench model, projected on the actual surface

5.3.2.5 Inform operator of proper dimensional settings with respect to prior excavation plan. (FR36)

The LiDAR sensor on the vehicle scans the environment in real time, allowing a reconstructed 3D model of the terrain around the vehicle to be displayed on the touch-screen. In conjunction with the visualization of the intended excavation geometry (see FR35 above), this allows the operator to perform a plausibility check for the planned excavation by comparing the actual and target environments.

5.3.2.6 Inform operator of successful calibration of excavator GNSS system and moving parts. (FR37)

In the scope of the project, we assume that calibration is automatically executed and diagnosed. Calibration itself occurs on the basis of data from the GNSS system and onboard IMUs. Since there is no automated tool recognition system, the GUI should prompt the operator to manually set the tool being used (e.g., loading it from a menu of presets) and inform them of the tool currently assumed to be in use during the calibration.
The GUI informs the operator that the calibration of the excavator moving parts has been successful. This information is displayed in a confirmative matter on the display.

5.3.2.7 Inform operator of distance to the target excavation depth. (FR38)

The bucket position is tracked in real time as described previously. Since the target excavation depth is known once an intended excavation geometry has been set (see FR35 above). The touch-screen shows the target depth as well as the current location of the bucket in the 3D visualization, allowing the operator to assess the remaining distance or possible overshoots. Furthermore, an LED matrix display mounted on the excavator arm and in-cabin HUD display show the current deviation from the target depth as a color-coded gauge (K in Figure 36).
Furthermore, the GUI could provide an explicit figure for the distance to the target excavation depth. This information is provided to the operator so that he knows if he has dug to far or still needs to dig deeper.

5.3.2.8 Inform operator of bucket fill level. (FR39)

The added value from informing the operator of the exact bucket fill level appears rather minimal, with the only conceivable use-case for this being a task where an exact mass needs to be loaded using the excavator. Also, while it is technically possible to retrieve this information from existing sensors on the excavator (pressure sensors in the hydraulics), the engineering involved is non-trivial, not state of the art, and outside the scope of the THEIA^{XR} project. Therefore, it does not appear sensible to seek to implement this function.

5.3.2.9 Provide operator with an unobstructed view of the surroundings. (FR310)

Cameras mounted on the vehicle provide 270° of coverage towards the left, right and rear. Coverage towards the front is not needed as this is naturally within the field of view of the operator. The images from these cameras can either be displayed independently or in a stitched form on the touch-screen.

5.3.2.10 Inform operator of an immediate danger or persons in the vicinity. (FR311, FR312)

Known dangers, in particular subsurface pipes and electrical lines, can be incorporated into the digital model of the environment and thus displayed or highlighted on the touch-screen 3D environment display. Furthermore, the HUD or LED-matrix displays can be used to provide indications of the remaining distance to these known dangers (K in Figure 36).

In order to detect people in the danger zone, the cameras mounted on the vehicle feed into computer vision algorithms allowing detection of persons. Models of the persons can then be added to the 3D visualization of the environment shown on the touch-screen and highlighted therein. Furthermore, the ambient light system could indicate a person in the vicinity by e.g., blinking red in the region corresponding to the direction in which the person is located.

Based on the sensor information described above, the onboard software can detect a danger and the GUI can inform the operator that a dangerous situation has been detected, as well as what is causing this danger. The GUI changes its layout (e.g., red color, blinking, noise) informing the operator that an immediate danger (a detected person which is causing a potential collision) is in the vicinity. If the direction from where the danger is coming is known, the GUI could potentially inform the operator where the danger is (see Figure 38).

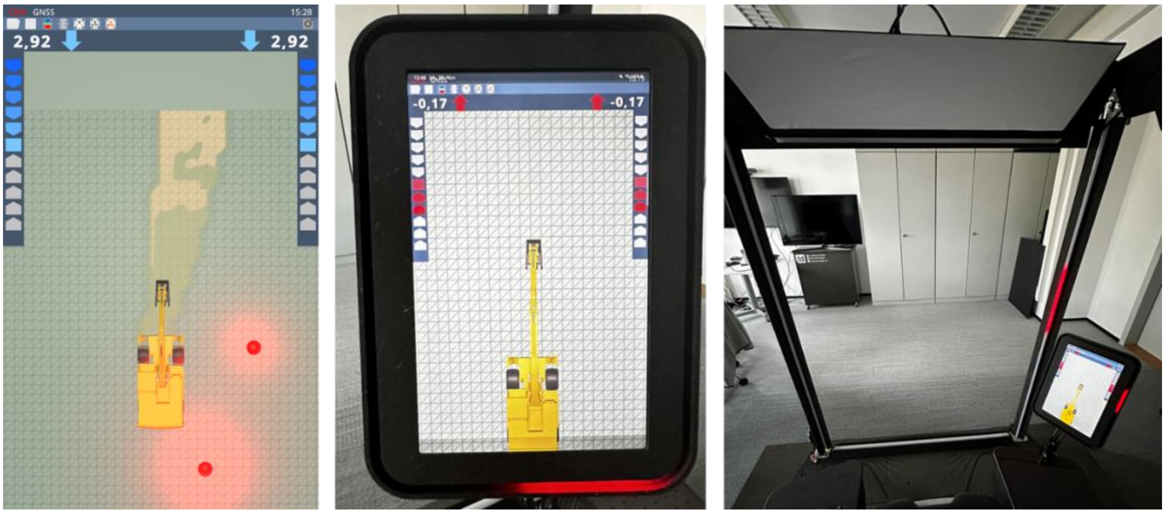

Figure 38: Different modalities for the visualization of a detected person (Visualization in the 3D model, ambient light around the display, ambient light at the a-pillar of the cabin)

5.3.2.11 Inform operator of successful activation of environment warning system. (FR313)

The GUI changes its configuration (e.g., layout) as soon as the environment warning system has been successfully activated.

5.3.2.12 Inform persons around of excavation in progress. (FR314)
Outer ambient lights mounted on the vehicle could inform people that they have been detected as being within the danger zone through blinking and or color changes.

5.3.2.13 Inform persons around of exact limits of danger zone (slewing radius). (FR315)
Testing has shown that envisioned laser projection systems for showing the slewing radius will likely not function as intended. However, the outer ambient lights described above for function FR314 could also be used to provide an indication of slewing direction to persons in the vicinity. Combined with the indication of detection in FR314, this would give persons in the vicinity implicit information about the dimensions of the danger zone.

5.3.2.14 Inform operator that the vehicle is powered down. (FR316)
The GUI in the machine changes configuration (e.g., brings up a message) stating that the vehicle is powered down. No functionality that can move the machine is activated anymore.

5.3.2.15 Inform operator that the excavator is aligned with intended digging direction. (FR317)
We do not intend to implement automated assessment of proper vehicle alignment. The digging outline is displayed as a virtual model along with the scanned environment in the 3D view shown on the touchscreen. This allows the operator to judge misalignment. Furthermore, the area of reach can also be displayed as an overlay on this 3D visualization to inform the operator of how far they have to drive back in order to efficiently continue the excavation.

5.3.2.16 Inform operator about successful activation of trench assistance system. (FR318)
In response to the operator activating the function, the GUI informs the operator (e.g., notification pop up), that the trench assistance system is successfully activated. Potentially, the layout of the GUI changes as long as this assistance system is active, showing function-specific controls and information fields. These controls allow the operator to adjust the centerline, width and slope, which are immediately shown to the operator on the 3D model.

5.3.2.17 Inform operator about the location of the edges of the trench. (FR319)
The operator teaches the location of the edges of the trench to the system using the bucket, tracked through a combination of vehicle location (measured with GNSS) and vehicle pose estimated from the kinematic model and current vehicle link IMU and slewing gear rotary encoder measurements.

The GUI can inform the operator if the bucket is passing the edges of the trench. The system knows where the edges are and by informing the operator that he passes an edge (e.g., highlighting on the screen), the operator is informed or reminded about their locations.

5.3.2.18 Inform operator about ideal unloading area. (FR320)
The ideal unloading area could be defined beforehand in the digital terrain model (DTM). Thus, displaying the digital terrain model (DTM) on screen allows the operator to know where the ideal unloading area is.

5.3.2.19 Inform operator about the zone to be left free for vehicle tracks to drive on. (FR321)
Similarly to the ideal unloading area, the zone to be left free for the vehicle tracks to drive on could be automatically added to the DTM or be previously defined in the DTM. Based on the position of the vehicle (i.e., GNSS), the vehicle knows when a certain area is reached. If it reaches a zone that needs to be left free, the GUI informs (e.g., coloring, message pop up, sound), that it reaches an area where it shouldn’t be.

5.3.2.20 Inform operator about reaching desired excavation depth. (FR322)
Based on the information from the sensors (i.e., GNSS, IMUs), the depth can be calculated. The display will highlight (e.g., in colors) if the desired depth is reached, or if the operator has dug too deep (see Figure 39). The HUD and LED-matrix display (see also K in Figure 36) indicating the remaining distance to the target depth (FR38) can also change color to indicate the desired depth has been reached.

Figure 39: Different modalities to visualize the correct digging depth (3D-model, LED-matrix display, HUD, augmented video-stream)

5.3.2.21 Inform operator about the quantity of scooped soil. (FR323)

This function does not appear sensible to implement (see remarks on FR39 above).

5.3.2.22 Inform operator that the bucket load is approaching or has reached critical weight. (FR324, FR325)

Assuming that there are sensors available that can measure this, the GUI highlights (e.g., with a pop-up message, color) the critical weight of the bucket load is approaching.

5.3.2.23 Inform operator of current machine efficiency (FR326)

Online efficiency assessment is very challenging, because of machine versatility and task diversity. => we focus on displaying vehicle parameters to the operator & let them decide

5.3.2.24 Inform operator of successful retraction of all hydraulic cylinders. (FR327)

Given that the operator is provided an unobstructed view to the boom and arm (FR310), he can visually assess that the bucket is safely placed on the ground and does not need to be informed about this further. This is a trivial task where the risk of failure is too low to make additional feedback to the operator sensible.

5.3.2.25 Inform operator of successful safe placement of bucket on the ground (FR328)

Given that the operator is provided an unobstructed view to the bucket (FR310), he can visually assess that the bucket is safely placed on the ground and does not need to be informed about this further. This is a trivial task where the risk of failure is too low to make additional feedback to the operator sensible.

5.3.2.26 Inform operator that all moving parts are locked. (FR329)

Since the operator "locks" the movement by pulling the safety lever, he is immediately aware of the execution of this function and does not require further feedback to be informed about it. The safety lever physically blocks the operator from leaving the vehicle, thus removing any conceivable risk of leaving the vehicle with moving parts unlocked. Further feedback is therefore not required.

5.3.2.27 Inform operator that the engine is off. (FR330)

The display provides a pop-up message informing the operator that the engines are turned off. This is triggered by internal software. Also, functionalities to control the machine are no longer available. The operator can further assess that the engine is off because the engine noise has ceased.

5.3.2.28 Inform operator of XR assistance system shutdown (FR331)

The in-cabin display shows a notification to the operator, indicating that the XR assistance system has been shut down. Furthermore, all XR visualizations are no longer available.

5.4 UC3 Demo specification

The playable demonstration for the excavator use-case will be developed under the heading of Creanex, who are in the process of building a virtual environment capable of hosting both physical and simulated UI elements showcasing the control and feedback functions previously discussed.

As for the other two use-cases, we begin by presenting the virtual environment, vehicle, and giving an overview of the simulated sensor data that may be available. We then separately discuss the physical UI elements that will be required for interacting with this demo, based on work from deliverable D5.5. We follow this with a discussion of simulated UI elements necessary to completely cover the spectrum of control and feedback functions we wish to evaluate. Finally, we recap the sequence of actions and events from the deliverable D3.2 scenarios that we plan to use as the simulation scenario.

5.4.1 Virtual environment, vehicle simulation and sensor data simulation

The excavator simulator is based on Creanex simulation platform. The working environment is an artificial construction site (see Figure 40) with which the virtual excavator interacts. Joysticks and pedal inputs are converted to virtual joint torques which move the machine parts. Counter forces are computed on the contact points between excavator and environment and also have an effect on the movement of the virtual machine parts. The ground surface of the working area is modelled by a dense triangular mesh, whose shape can be updated in real-time to visualize excavation of holes and ditches.

Figure 40: Excavator in simulated environment

The top-level architecture of Creanex simulator platform is presented in Figure 18 of Section 3.4.1.

Creanex simulation platform and available features for sensor simulations and other capabilities are presented in deliverable D4.5.

5.4.2 Physical UI elements

The movement of the machine is controlled by joysticks and pedals. The functions described above in Sections 5.2 and 5.3 will make use of physical touch-screens provided by TTC (see also Figure 19) and ambient light system provided by TUD. The physical hardware interfacing with the simulation is described in detail in deliverable D5.5.

5.4.3 Simulated UI elements

For demonstrating the UC3 interaction concepts, it is planned to use physical assets primarily. However, it might be helpful to embed a simulated version of the external LED-Matrix display (functions FR34, FR38, FR311, FR312, FR322) which is attached to the excavators' boom for space reasons.

The UI projections on the windscreen (see functions FR33, FR34, FR38, FR311, FR312, FR322) may also need to be simulated as the hardware to implement them might not be readily available in the THEIA^{XR} project.

6 Conclusions

This first version of deliverable D4.4 described the interaction model used for ideating control and feedback functions, along with a first version of specifications for the expected set of immersive playable demonstrations to be developed to showcase the control and feedback functions ideated within the project.

We begin by an analysis of the current versions of the use-case scenarios provided by deliverable D3.2 following an interaction model in which any event in an operation scenario requires either the implementation of a control function, the implementation of a feedback function, or both. Control functions imply that the operator uses a UI element to trigger and control an action executed by the vehicle, tool or UI. Thus, a specific mapping of UI element input values to vehicle, tool or UI setpoints or states must be defined. Similarly, feedback functions require the vehicle's internal software and sensors to acquire sensor values, process them in a defined manner, and map the resulting values to outputs on a UI element. The feedback mapping must therefore be defined in a similar manner to the control mapping.

This approach allowed us to decompose the scenarios into component actions and events, each of which imply a set of component control and feedback functions. Once the set of unique control and feedback functions was established, we described the current state of ideation and implementation of concrete proposals for realizing them. The results described in the present version of the deliverable reflect ongoing work on this subject and will therefore be subject to change as insights are gathered through design and testing.

Future work on this deliverable will begin by refining the list of component control and feedback functions based on the finalization of the scenarios produced in deliverable D3.2. Together with insights gained through the co-design process involving operators for all three use-cases, this will yield a final list of functions considered sensible. Based on the final D3.2 scenarios and this list of functions, we will agree on demo scenarios for each of the three use-cases and verify that implementation proposals have been gathered for all control and feedback functions concerned. In parallel, partners will continue to refine their designs for the respective control and feedback functions they proposed, so as to converge towards practical demo implementations of each function to be included in the final demonstrators. The final step will consist in integrating these functions into the three demonstrators developed under the heading of CREA (UC1 and UC3) and VTT (UC2) respectively. This will allow us to produce a set of three immersive playable demonstrations showcasing novel control and feedback functions matching the results of the co-design process conducted in work package WP3.

References

[1] Al-Fedaghi, S. (2012). *A conceptual foundation for the Shannon-Weaver model of communication*. International journal of soft computing, 7(1), 12-19.

[2] Proctor, R. W., Thomas, B. S., & Dunston, P. S. (2022). Human Interactions with an Excavator Simulator: Assessing Two Patterns of Joystick Control Mappings. In *Human-Automation Interaction: Manufacturing, Services and User Experience* (pp. 579-596). Cham: Springer International Publishing

[3] https://www.ti.com/lit/ds/symlink/drv2605.pdf?ts=1708437852271 (RETRIEVED: 17/02/2024)

ABBREVIATIONS / ACRONYMS

[CAN]	Control Area Network
[DTM]	Digital Terrain Model
[ECU]	Electronic Control Unit
[GNSS]	Global Navigation Satellite System
[GUI]	Graphical User Interface
[IPC]	Industrial Personal Computer
[KPI]	Key Performance Indicator(s)
[LiDAR]	Light Detection and Ranging
[RC]	Remote-Controlled
[UC]	Use-Case
[UI]	User Interface
[WP]	Work Package
[XR]	eXtended Reality

7 APPENDIX

7.1 UC1 Control functions summary table

KEY	CONTROL FUNCTION
CR11	Operator starts the engine.
CR12	Operator activates vehicle diagnostics.
CR13	Operator activates navigation assistance system.
CR14	Operator drives vehicle.
CR15	Operator adjusts blade settings.
CR16	Operator adjusts tiller settings.
CR17	Operator triggers the haptic guidance for blade or tiller positioning.
CR18	Operator reverses vehicle.
CR19	Operator collects snow.
CR110	Operator transports snow.
CR111	Operator repairs damaged surface.
CR112	Operator activates "poor visibility support" system.
CR113	Operator activates 3D visualization of vehicle position on slope.
CR114	Operator drives winch winding.
CR115	Operator activates smart spotlight.
CR116	Operator directs smart spotlight direction.
CR117	Operator activates environment warning system.
CV11	Operator puts on the XR helmet.
CV12	Operator selects and connects to his vehicle.
CV13	Operator selects suitable camera view.

Table 11: Component control functions envisioned in UC1

7.2 UC1 Feedback functions summary table

KEY	FEEDBACK FUNCTION
FR11	Inform operator of safe machine state.
FR12	Inform operator about successful engine start.
FR13	Inform operator of pending maintenance.
FR14	Inform operator of unsuitable state of vehicle for intended use.
FR15	Inform operator about vehicle width.
FR16	Inform operator about vehicle alignment.
FR17	Inform operator about location of work area.
FR18	Inform operator that work area has been reached.
FR19	Inform operator about current blade settings and state.
FR110	Inform operator about discrepancies between current blade settings and optimal calculated blade settings.
FR111	Inform operator about current tiller settings and state.
FR112	Inform operator about discrepancies between current tiller settings and optimal calculated tiller settings.
FR113	Inform operator about recommended speed.
FR114	Inform operator about recommended tiller pressure.
FR115	Inform operator about incorrect blade settings.
FR116	Inform operator about excess snow digging depth.

FR117	Inform operator about damage to slope.
FR118	Inform operator about available excess snow to be used for repairs.
FR119	Inform operator about successful repair of damaged slope.
FR120	Inform operator about successful activation of the "poor visibility support" system.
FR121	Inform operator about vehicle dimensions relative to slope in poor visibility conditions.
FR122	Inform operator about bumps and obstacles in poor visibility conditions.
FR123	Inform operator about general condition of the ground.
FR124	Inform operator about the horizon location and orientation in poor visibility conditions.
FR125	Provide a 3D visualization of vehicle and slope to operator.
FR126	Inform operator about the presence of obstacles in the vicinity.
FR127	Inform operator about the nature of obstacles in the vicinity.
FR128	Inform operator about the distance and/or direction to obstacles in the vicinity.
FR129	Warn operator that winch is required.
FR130	Inform operator about successful winch anchoring.
FR131	Inform operator about winch cable tension.
FR132	Inform operator about winch cable path or direction.
FR133	Inform operator about a hazard in winch operating area.
FR134	Inform operator about the direction towards or location of a hazard in the vicinity.
FR135	Inform operator of successful activation of the environment warning system.
FR136	Inform persons in vicinity of the danger zone around the vehicle.
FR137	Inform operator about progress on or completion of planned work.
FV11	Provide operator with a view "through the snowgroomer's eyes"
FV12	Inform operator about ideal route to work area.
FV13	Inform operator about progress along a route.
FV14	Inform operator about insufficient slope quality.
FV15	Provide operator with rear view towards finished slope

Table 12: Component feedback functions envisioned in UC1

7.3 UC2 Control functions summary table

KEY	CONTROL FUNCTION
CR21	Operator logs into the RC console system / Operator identifies himself in the RC console system.
CR22	Operator checks that the RC console indicator lights are working.
CR23	Operator contacts service personnel.
CR24	Operator activates the RC console in order to establish the connection to the reach stacker
CR25	Operator switches on the working lights of the RS.
CR26	At workshop or parking place, the maintenance person checks the machine visually.
CR27	Operator starts the engine if it is not already running
CR28	Operator checks the status of the machine from the PC screen and videos
CR29	Operator switches the machine to auto mode.
CR210	The machine steers itself out of the parking area.
CR211	Operator checks job information. (tentative: may not require operator's input)
CR212	Operator selects job and the status of the machine and video screens
CR213	Drive machine to target location
CR214	Operator checks for safety before moving the spreader. (tentative: this may not require operator input)
CR215	Operator maneuvers spreader and boom.
CR216	Operator moves and extends spreader (manual extension or toggle between preset positions).
CR217	Operator engages/disengages twist locks.
CR218	Operator triggers vehicle reverse movement

CR219	The system checks truck license plate with OCR.
CR220	Operator switches the machine to RC mode
CR221	Operator adjusts cabin position.
CR222	Operator aligns the stacker with the container or trailer position.
CR223	The system automatically adjusts camera views.
CR224	Operator triggers AutoLock function.
CR225	Operator disconnects RC console from reachstacker
CR226	Operator triggers emergency stop
CV21	Automatic adjustment of seat height etc. based on personal settings.
CV22	Operator selects assigned harbor terminal.
CV23	Operator selects assigned vehicle.
CV24	Operator switches camera view.
CV25	Operator triggers vehicle function diagnostics.
CV26	Operator calls up minimap.
CV27	Operator triggers XR assistance
CV28	Operator activates width visualization function.
CV29	Operator puts the vehicle into standby
CV30	Operator calls up personal performance dashboard
CV31	Operator calls up job playback function.

Table 13: Control functions identified in the UC2 scenarios

7.4 UC2 Feedback functions summary table

KEY	FEEDBACK FUNCTION
FR21	Inform operator of successful log-in (or Inform operator of the operator ID recognized via the token)
FR22	Inform operator of functional RC console indicator lights.
FR23	Provide audio communication to service personnel.
FR24	Inform operator of successful activation of the RC console
FR25	Inform operator of successful connection to the reach stacker
FR26	Inform operator of preset vehicle settings associated with recognized operator ID
FR27	Inform operator that personalized vehicle settings have been successfully applied.
FR28	Provide Operator with machine operation view.
FR29	Inform operator that RS working lights are switched on
FR210	Inform operator of vehicle operational state.
FR211	Inform operator of vehicle safety.
FR212	Inform operator of successful engine start
FR213	Provide multiple camera views of vehicle in parking area.
FR214	Inform operator of successful activation of auto mode
FR215	Inform operator of successful activation of RC mode
FR216	Inform operator about list of assigned orders / pending jobs
FR217	Inform operator about successful selection of a job.
FR218	Inform operator of the current job details and overview.
FR219	Provide operator with the layout or minimap of the port in the vicinity of the vehicle / in the job area
FR220	Provide operator with multiple and/or selected camera views (incl. rear view) to vicinity of the vehicle
FR221	Alert operator to approaching machine
FR222	Inform operator about safe space available for extending spreader
FR223	Inform operator about current set spreader size
FR224	Provide operator with unobstructed view towards the vehicle vicinity, spreader and container

FR225	Inform operator about horizontal and vertical distance between twist locks and container corners
FR226	Inform operator that twist locks can safely be engaged/disengaged
FR227	Inform operator that twist locks have successfully been engaged/disengaged.
FR228	Inform operator that vicinity is clear for reversing.
FR229	Inform operator that boom and spreader are in a suitable position for driving.
FR230	Inform operator about truck ID in loading order
FR231	Inform operator about ID of truck currently being loaded
FR232	Inform operator about ideal loading position and orientation relative to truck being loaded.
FR233	Inform operator of discrepancies between container actual and ideal position for loading.
FR234	Inform operator that container has been sufficiently lowered to allow release.
FR235	Inform operator that spreader has cleared the container.
FR236	Inform operator of the presence of persons in the vicinity of the vehicle
FR237	Provide operator with clear vision and earshot of the vehicle vicinity
FR238	Inform operator that spreader has reached a preset position.
FR239	Inform operator of current camera position.
FR240	Inform operator that ideal or desired driver cab position has been reached
FR241	Inform operator that spreader has reached suitable position for picking / lowering container
FR242	Inform operator that spreader has been sufficiently lowered to allow AutoLock function to run
FR243	Inform operator that AutoLock has successfully been carried out.
FR244	Inform operator that container is ready to be lifted
FR245	Inform operator that the boom and spreader are in a suitable position for transport.
FR246	Inform operator that the job is complete
FR247	Inform operator that RS is safely stopped and ready for disconnect.
FR248	Inform operator that RC console is disconnected from reachstacker
FV21	Inform operator about assigned harbor terminal.
FV22	Inform operator about selected harbor terminal
FV23	Inform operator about assigned vehicle.
FV24	Inform operator about selected vehicle.
FV25	Provide dashboard of the vehicle's parameters (fuel, oil temperature, gearbox temperature)
FV26	Inform operator about ideal route to target location.
FV27	Inform operator about distance to the target location.
FV28	Inform operator about current driving functions being executed (acceleration, braking, steering)
FV29	Inform operator about relative position of objects and vehicles in the environment.
FV210	Inform operator about distance to objects and vehicles in the environment.
FV211	Inform operator about predicted trajectory of vehicles in the environment.
FV212	Highlight target container or truck in augmented camera view.
FV213	Provide operator with AR overlays on video during manual remote driving
FV214	Inform operator about container weight and/or center of mass.
FV215	Project the container limits or ideal loading position on the ground
FV216	Display persons in the vicinity on the minimap
FV217	Highlight persons in the vicinity in the camera views
FV218	Inform operator of relative width of vehicle + container to free space in which the vehicle navigates.
FV219	Inform operator of optimal path to follow in tight corridors of the port.
FV220	Inform operator that vehicle has successfully been put into standby.
FV221	Provide operator with a personal performance dashboard
FV222	Provide operator with a fast-forward playback of the day's driving path
FV223	Inform operator of successful logout of the RC desk.

Table 14: Feedback functions identified in the UC2 scenarios

7.5 UC3 Control functions summary table

KEY	FEEDBACK FUNCTION
CR32	Operator calls up systems diagnostics test.
CR33	Operator drives the excavator to a defined location.
CR34	Operator orients the excavator with respect to a defined target location.
CR35	Operator calls up a visualization of the planned excavation on screen.
CR36	Operator adjusts the dimensions of the planned pit.
CR37	Operator digs into soil.
CR38	Operator scoops up load of soil
CR39	Operator swings and moves bucket
CR310	Operator unloads to an intended location on the side.
CR311	Operator empties bucket.
CR312	Operator interacts with warning system
CR313	Operator activates the environment warning system.
CR314	Operator powers down the vehicle temporarily.
CR315	Operator rotates the excavator.
CR316	Operator teaches the outline of the trench by moving the bucket to the outline positions
CR317	Operator enters / adjusts the dimensions of the trench.
CR318	Operator works on trench and repositions excavator
CR319	Operator triggers XR visualization of the trench.
CR320	Operator reverses the vehicle by a defined distance.
CR321	Operator scoops up (heavy) load of soil / Operator increases the quantity of soil being scooped up.
CR322	Operator activates machine efficiency monitoring.
CR323	Operator retracts hydraulic cylinders.
CR324	Operator places bucket on the ground.
CR325	Operator locks all moving parts.
CR326	Operator powers down the engine.
CR327	Operator powers down the XR assistance.
CV31	Operator starts up the XR assistance
CV32	Operator activates the trench assistance system

Table 15: Control functions identified in the UC3 scenarios

7.6 UC3 Feedback functions summary table

KEY	FEEDBACK FUNCTION
FR31	Inform operator of the engine status.
FR32	Inform operator of system functional state.
FR33	Inform operator of functional state of the XR assistance.
FR34	Inform operator of reaching a desired vehicle position/orientation.
FR35	Inform operator of intended excavation geometry.
FR36	Inform operator of proper dimensional settings with respect to prior excavation plan.
FR37	Inform operator of successful calibration of excavator moving parts.
FR38	Inform operator of distance to the target excavation depth.
FR39	Inform operator of bucket fill level.
FR310	Provide operator with an unobstructed view of the surroundings.
FR311	Inform operator of an immediate danger in the vicinity.
FR312	Inform operator of the presence of persons in the vicinity.
FR313	Inform operator of successful activation of environment warning system.

FR314	Inform persons around of excavation in progress.
FR315	Inform persons around of exact limits of danger zone (swiveling radius).
FR316	Inform operator that the vehicle is powered down.
FR317	Inform operator that the excavator is aligned with intended digging direction.
FR318	Inform operator about successful activation of trench assistance system.
FR319	Inform operator about the location of the edges of the trench.
FR320	Inform operator about ideal unloading area.
FR321	Inform operator about the zone to be left free for vehicle tracks to drive on.
FR322	Inform operator about reaching desired excavation depth.
FR323	Inform operator about the quantity of scooped soil.
FR324	Inform operator that the bucket load is approaching critical weight.
FR325	Inform operator of the critical load.
FR326	Inform operator of current machine efficiency.
FR327	Inform operator of successful retraction of all hydraulic cylinders.
FR328	Inform operator of successful safe placement of bucket on the ground.
FR329	Inform operator that all moving parts are locked.
FR330	Inform operator that the engine is off.
FR331	Inform operator of XR assistance system shutdown.

Table 16: Feedback functions identified in the UC3 scenarios