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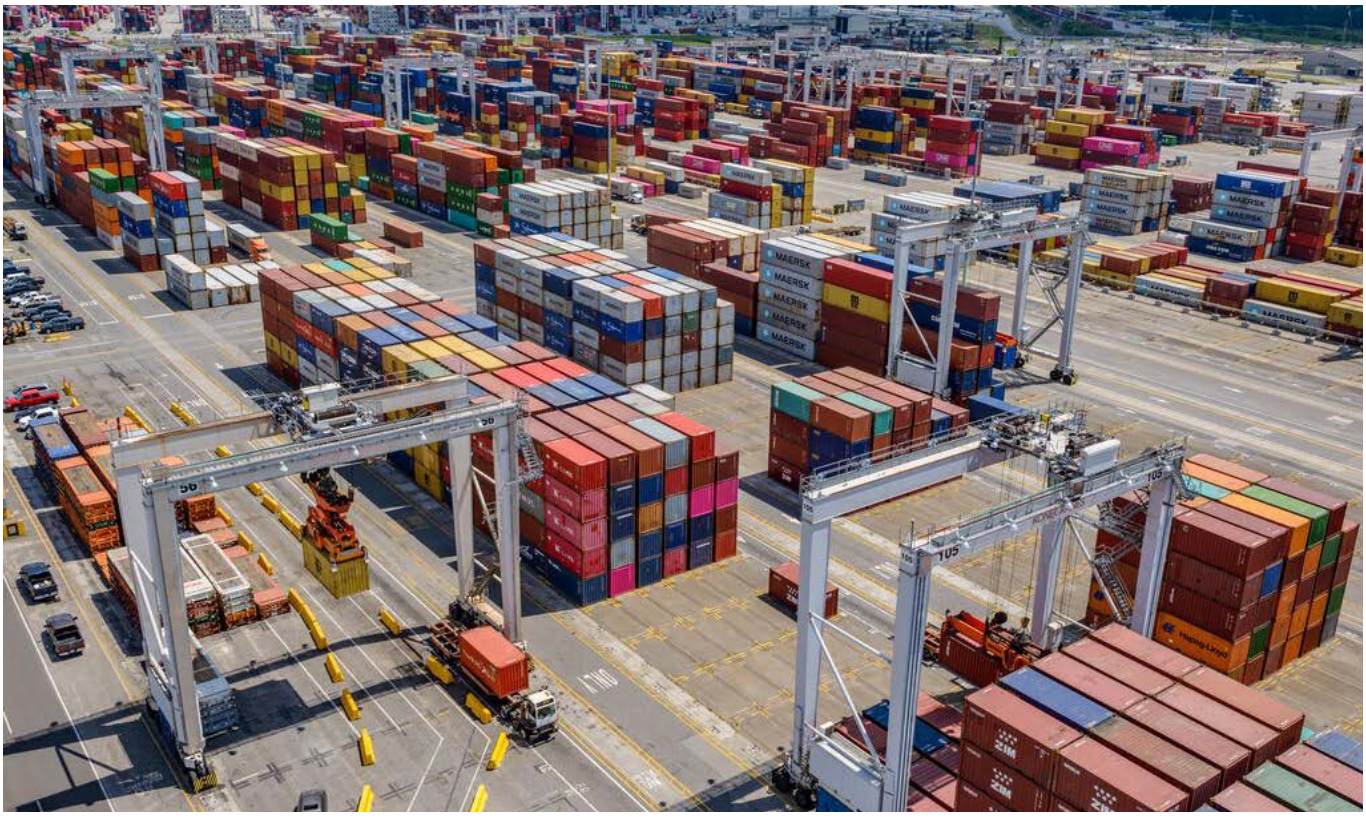
Mixed Mode Automation

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1. Introduction

In 1993, one of the first automated terminal using unmanned RMG cranes was opened at the ECT Delta Terminal in Rotterdam. Inspired by the success of this landmark project, the concept was adopted worldwide. The design of ECT Delta and many similar terminals is based on the end-loaded stack configuration layout, which strictly isolates the automated section of the terminal from other vehicles, such as, road trucks. This separation between unmanned and manually driven vehicles has been the starting point for many port automation projects. The disadvantage of strict separation is that it may lead to inefficient land use and higher infrastructure costs due to fencing and dedicated driving lanes. A high transhipment ratio may be a factor in terminals selecting a quay-parallel container stack layout utilising cantilever-stacking cranes rather than an end-loaded stack configuration. In this stacking arrangement, all cranes can effectively support both landside and waterside operation, but strict separation of road trucks and internal horizontal transport vehicles is no longer possible.

In recent years, demand for more flexible automation has increased. Developments in other industries, such as autonomous cars, have encouraged the idea that AGVs and road trucks could share the same driving paths. Other stack layouts (e.g., side-loaded layout) also offer benefits but require that road trucks be allowed to drive under the gantry cranes, which may be unmanned. This kind of automation, in which unmanned and manned vehicles operate in the same areas rather than being strictly separated, is referred to as “Mixed Mode Automation” in this paper.

The main barrier to implementing such flexible automation has been safety concerns. If unmanned equipment and people-driven vehicles are allowed to operate near each other, special arrangements, sensors, and fail-safe systems are required to ensure safe operation. Remote control of cranes has been used as one tool to handle dedicated safety-critical parts of operations, but this approach increases the number of personnel required to operate the fleet.

This information paper provides a summary of the current trends, technologies and safety requirements of Mixed Mode Automation. One key topic is Horizontal Transport of containers and the use of common pathways between AGVs and manned vehicles. Another key topic is the Interchange Areas, where the container handover from a horizontal transport vehicle (manned road truck) to a stacking crane (unmanned ARTG/ARMG crane) takes place.

1.1 Approaches to Safety in Mixed Mode Automation

At the outset, it is worthwhile to define basic conceptual approaches for possible solutions, and two complementary approaches are considered.

The first approach is to determine the positions of all objects (machines and people) within the working area of all machines. If this information is available with 100% accuracy, the machines can be controlled in such a way that collisions are not possible.

The second approach is where the machines scan their environment for possible collisions when in motion, i.e. when the machine moves – horizontally or vertically – the environment is scanned for the presence of people or objects.

It is advisable to use both concepts in a complementary way to achieve an optimal solution.

In approach 1, all machines and personnel must be equipped with position-detection sensors.

For example, transponders can be installed in the terrain, with corresponding antennas on the machines. Alternatively, GPS (Global Positioning System) or LPS (Local Positioning System) can be used, or the machines’ movements can be measured (odometry). Identification of personnel positions within machine GPS and LPS operating zones is only possible when personnel wear appropriate devices.

In addition to the position sensors, there is, of course, a need for a central intelligence (computer) to which position information from machines and people is

transmitted. A suitable data transmission technology must be utilised for this function. This central intelligence data processor must track all positions, detect potential collisions, send information back to the machines' control system to stop the machines, and send alarm messages to personnel in the field.

In approach 2, the environment around the machine must be monitored for the presence of subjects and objects before and during movement. Area-monitoring sensors, such as 3D laser scanner systems, detect violations of the area and send the required signals to the machine control system, which in turn controls the machine drives, brakes and stops the machine.

In summary:

Position-detection sensors, combined with central intelligence (computer), evaluate position and movement information. In the event of a collision risk, the appropriate action, alerting machines and personnel, is initiated.

Area-monitoring sensors on the machines, combined with the machine's automation logic. In the event of a collision risk, the automation logic will slow down the machine and ultimately stop it.

Safety is risk management:

In a Port environment, it is necessary to consider the following risks:

- **Harm risks** for people
- **Collision risks on critical infrastructure** (STS, RTG, Container, Vessel)
- **Risk of Blockage** (which could lead to service breakdown)
- **Security risks** that could lead to one or several of the above risks but also have privacy/ confidentiality impacts.

Here is a non-exhaustive list of situations to be considered in the risk management assessment procedure:

Port zones with different speed limits and traffic density requirements:

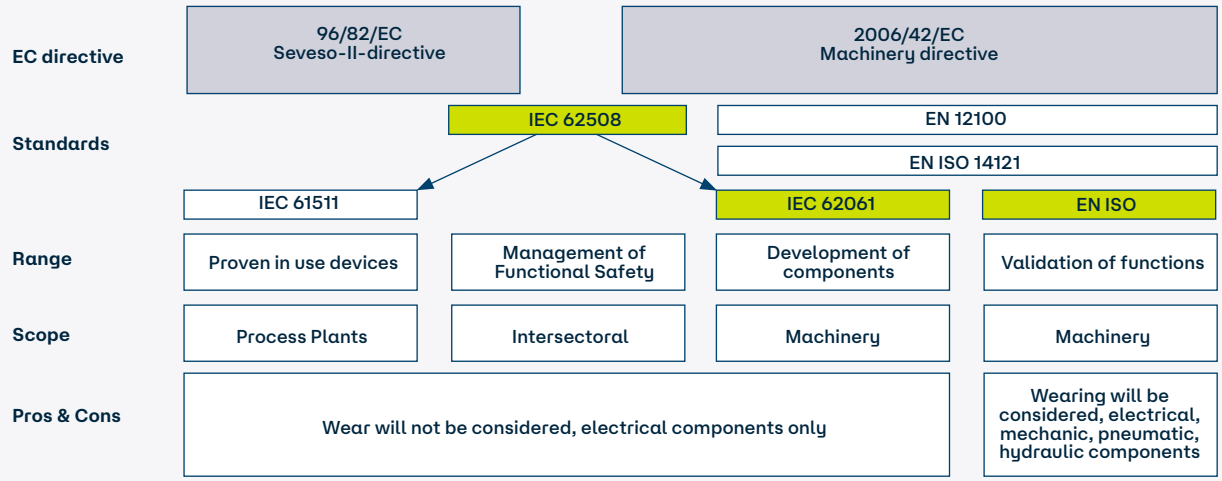
- Main access roads
- RMG Manoeuvring area
- RMG Transfer point
- RTG access lane
- RTG transfer lane
- STS transfer lane
- STS access roads
- Intersection between stacks
- Intersection of main roads.

Risk Analysis

Risks are formally analysed in accordance with IEC 61508 ('intersectoral scope'), as shown in ***figure 1***. IEC 61508 is a basic functional safety standard applicable across all industries. The fundamental concept is that any safety-related system must either work correctly or fail in a predictable (safe) way. Central to the standard is the concept of the probability of risk for each safety function: zero risk can never be achieved; only the probability can be reduced.

IEC 62061 and ISO 13849 are machinery-specific implementations of IEC 61508 and introduce the essential concepts of Safety Integrity Level **(SIL, IEC 62061)** and safety Performance Level **(PL, ISO 13849)**. In case of fatal risk scenarios, Safety Integrity Level "SIL 2" or Performance Level "PL d" is typically required. In minor risk cases, "PL c" can also lead to an acceptable risk mitigation.

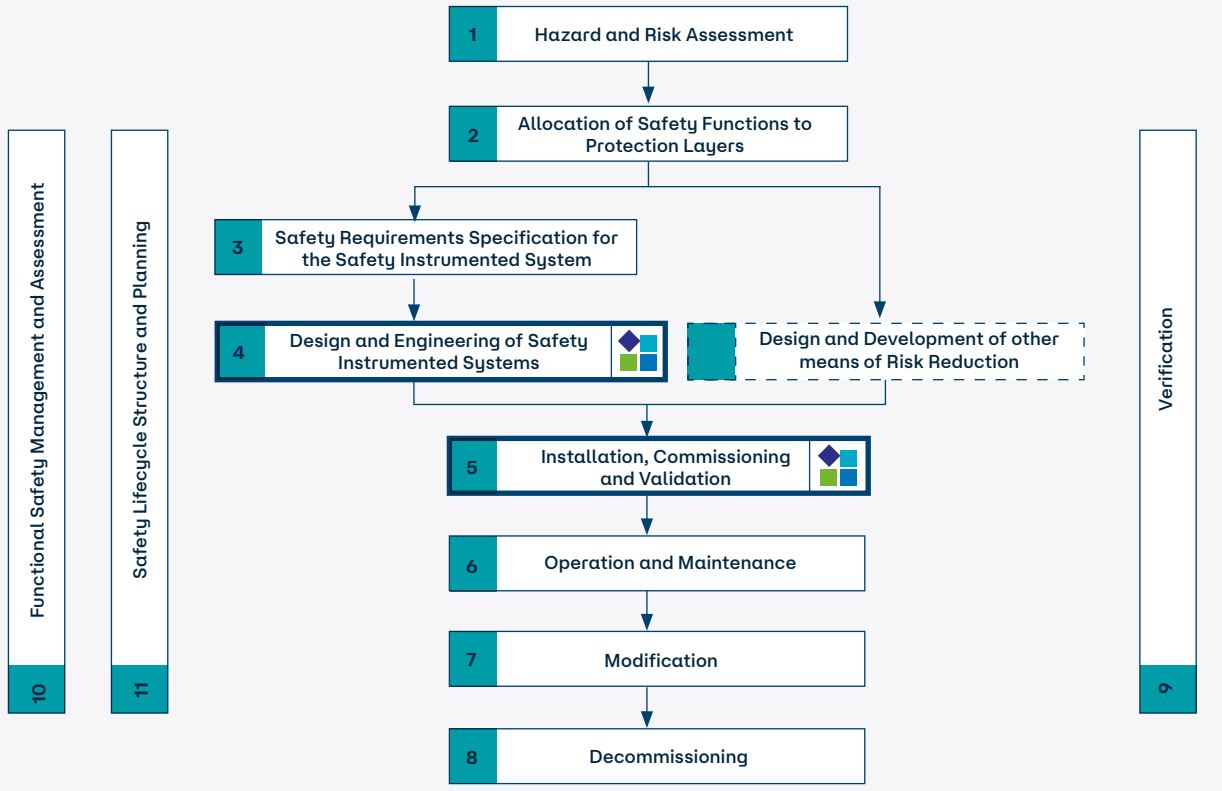
Fig 1: Risk Analysis



Safety Life Cycle

The development of the safety concept will follow the functional safety lifecycle, ***figure 2.*** An engineering process called the safety life cycle is defined based on best practices in order to discover and eliminate design errors and omissions. As a result, the user will also have a responsibility in this process.

Fig 2: Functional Safety Life Cycle



2. Sensors

Different sensors with different measurement methods can be used for the detection of people or for the localisation of objects and subjects.

While IEC 62061 and ISO 13849 address the main principles of functional safety, these standards do not cover specification or validation requirements for the safety-related detection capabilities of sensors. Such requirements are mandatory for safety-related detection sensors. Therefore, safety-related sensors must also be certified to an applicable standard for detection capabilities, such as IEC TS 62998-1, which serves as the counterpart to ISO 13849-1.

2.1 Laser-based Sensors

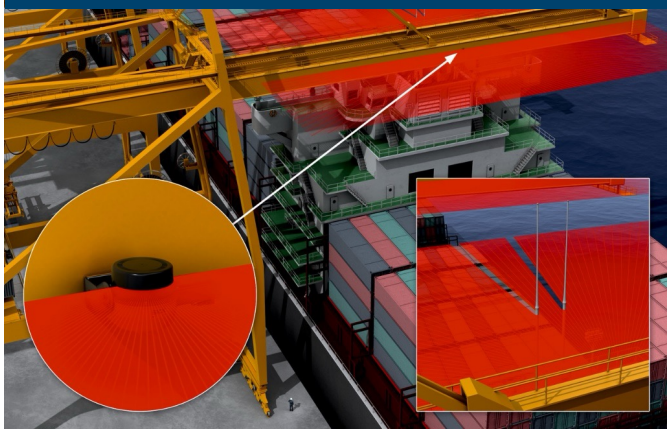
The basis for laser-based people and object detection solutions in the working area of machines (crane, AGV, straddle carrier, automated truck) is the use of 2D or 3D multilayer or solid-state laser scanners. These laser scanners generate either a 2-dimensional scanning plane or 3-dimensional spatial images. If a person enters the machine's monitoring or working area, the laser measurement system detects the person, and the machine's movement can be stopped.

Typical applications include collision avoidance and protecting people during machine travel by monitoring the travel path, or during the loading/unloading of a truck.

2.1.1 2D Laser Scanner

2D LiDAR sensors use laser light to measure distances and create a two-dimensional map of the environment. Compared to 3D sensors, the focus is often on high angular resolution and scanning frequency.

Fig 4: Typical Case Using 2D-Laser scanner for Boom Collision Prevention



Example of 2D-point cloud density

On a 2D scan plane, the laser point is emitted in angular steps of 0.02° (horizontal resolution), with a 360° aperture angle, a scanning frequency of 25 Hz, and a working range of up to 250m. The spot size depends on the working range, e.g., 30 m = 30x85mm, 80m = 200x350mm.

Fig 3: General Structure of Safety-Related Sensor System

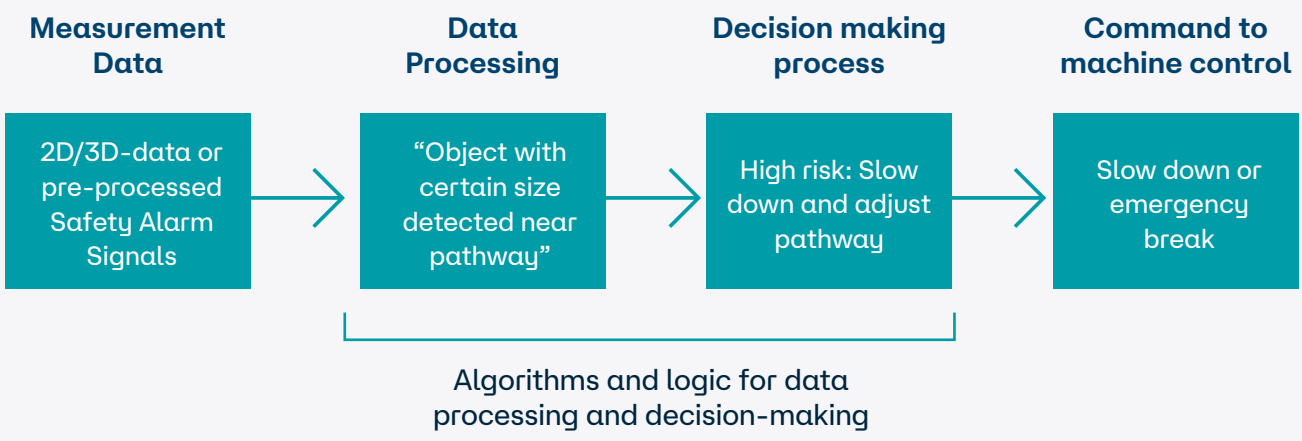
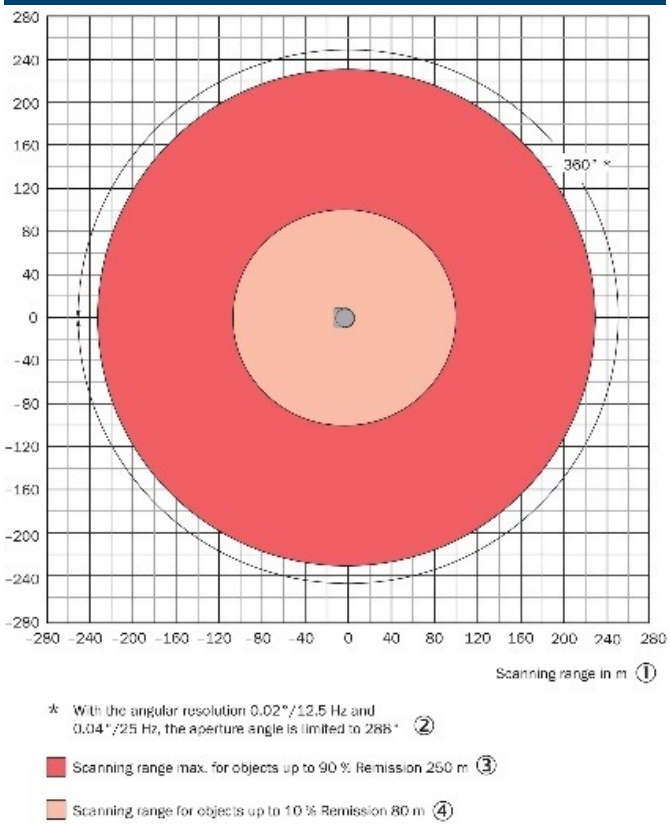


Fig 5: Example of 2D-point Cloud Density



On a 2D scan plane, the laser point is emitted in angular steps of 0.02° (horizontal resolution), with a 360° aperture angle, a scanning frequency of 25 Hz, and a working range of up to 250m. The spot size depends on the working range, e.g., 30 m = 30x85mm, 80m = 200x350mm.

2.1.2 Multi-layer Laser Scanner

Multi-layer laser scanners generate a large number of 2D scan planes. Lasers with 4 to more than one hundred scan planes are available on the market. Some sensors have a rotating optical unit, while others deflect the laser beam using moving mirrors. Depending on the application, aperture angles from 45° to 360° are possible.

In addition to the number of scan planes, the following criteria are important when selecting the right sensor:

- Distance
- Accuracy
- Horizontal scanning field
- Vertical scanning field
- Number of laser points in the scan plane, i.e. distance between scan points in the scan plane
- Divergence of the laser spot (dot size)

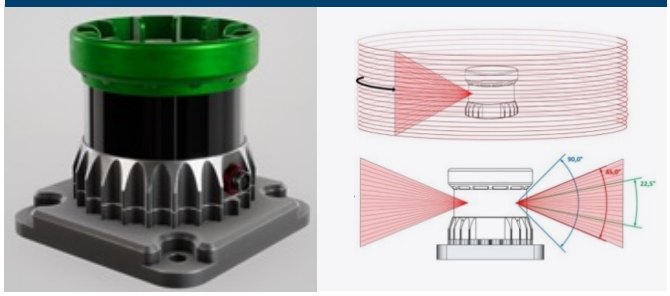
Two examples of point cloud density calculation are provided below:

Example 1

Within a 2D scan plane, the laser points are emitted at angular steps of 0.175° (horizontal resolution). If a laser scanner is measuring at a distance of 20 m, then the laser points are 61 mm apart. The horizontal scan planes have a range of 360°.

The scanner has a vertical scan angle of 45 degrees and 128 scan planes. The vertical resolution is 0.35°. This means that the scan planes are separated by 123 mm at a distance of 20 m.

Fig 6: Laser Scanner with the Laser Beam Characteristic



Example 2

Different variants of the vertical field of view (a) 65 degrees and (b) 42 degrees with 16 scan planes each and 360° horizontal aperture angle.

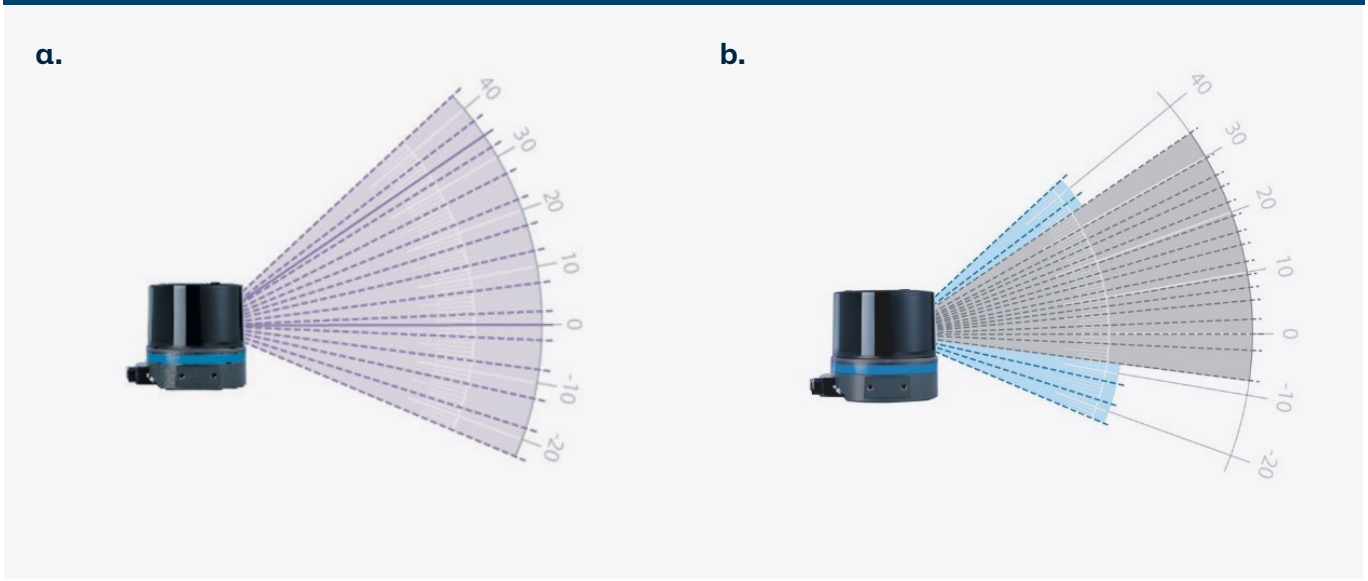
a. All 16 scan planes with a resolution of 0.5° and a scanning frequency of 20Hz. Working range up to 30m* at 90% reflection factor.

b. 2 scan planes with a resolution of 0.125° (at 0° scan plane optimised for mobile platforms) and 14 scan planes with a resolution of 1° and a scanning frequency of 20/40Hz. Working range up to 62m* at 90% reflection factor.

With the integrated interlaced mode, all scan planes can be output with a resolution of 0.125° depending on the output frequency.

* Detection probability > 99%

Fig 7: Laser Scanner with the Laser Beam Characteristic (a) and (b)



2.1.3 Solid State Laser

The solid-state laser has no moving parts within the sensor. The 3D laser source is chip-based. As with the Multilayer Laser scanner, a 3D scan pattern is generated, and the same criteria outlined in 2.12 must be used to select the appropriate sensor for the application.

2.1.4 Safety Certified Lasers and Systems

Safety certification of sensor-based systems can be achieved using both safety-certified and non-safety-certified sensors.

Safety-certified laser sensors (***figure 8, next page***) perform safety-certified area surveillance on the sensor itself, with a safe output to the higher-level system. These safety-related sensors provide defined functional safety features and are certified by a notified body. Furthermore, a certified outdoor safety sensor must include its defined limits of use, taking into account environmental factors such as rain, dust, and fog. In this regard, the detection capability (Performance Class in accordance with IEC TS 62998) is particularly relevant. Safety-related sensors can provide various safety functions, such as protective fields (internal logic, e.g., for detecting persons and triggering a safe state) and/or safety-related measurement data (enabling advanced or customisable safety functions via an external application processing unit, e.g., safety-related localisation and mapping).

Safety certification at the system level (***figure 9, next page***) is based on ISO 13849 and does not require the mandatory use of safety-certified sensors. When non-safety-certified sensors are used, the system integrator ensures system-level safety, and the overall system is safety-certified by the integrator.

Fig 8: Using Safety-Certified Sensors to Achieve a Safety Function

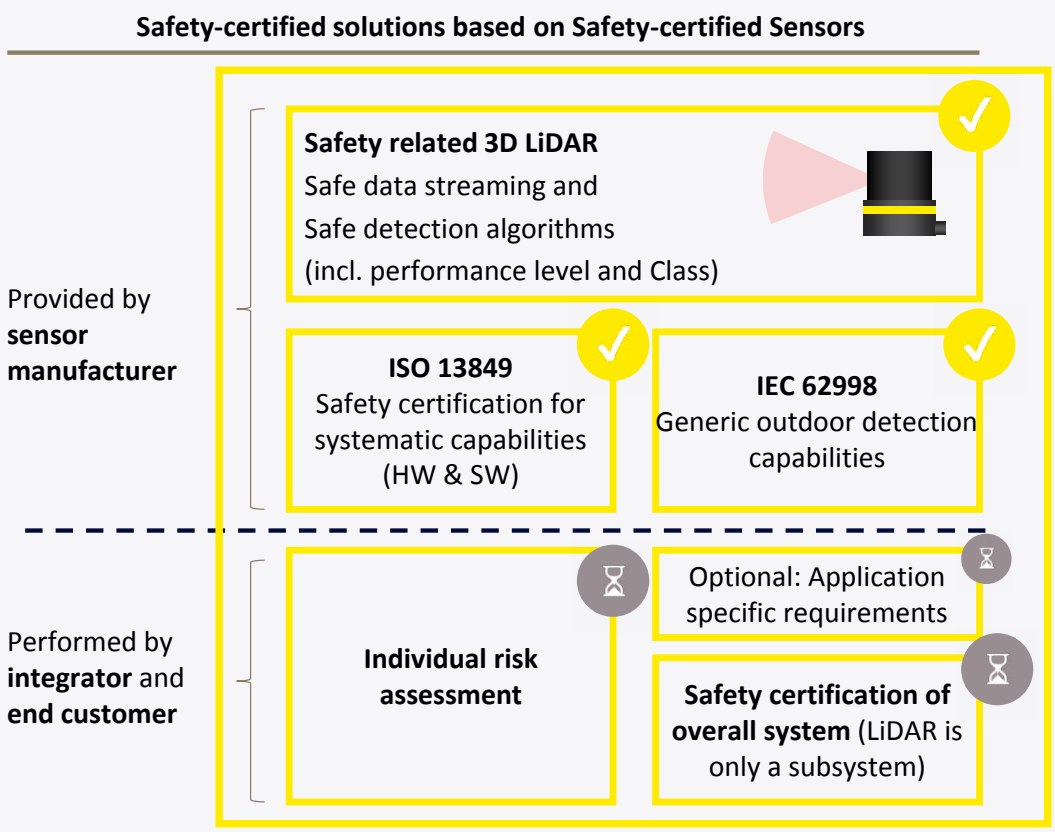
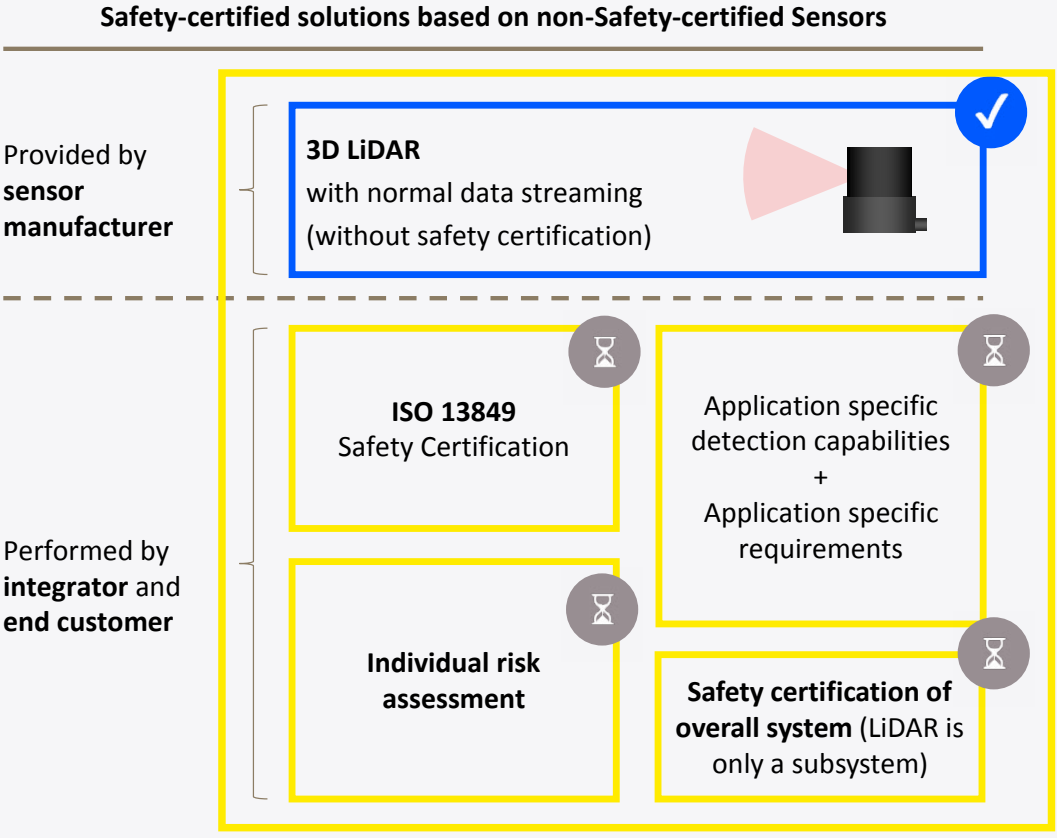


Fig 9: Using Standard Sensors to Achieve a Safe Solution



2.2 Radar-based Sensors

Microwave radar sensors can track several objects simultaneously (e.g. up to 40 objects at a 10 Hz rate) and provide a list of detected objects, including the strength of the echo (RSC, Radar Cross Section), distance, direction and the object's relative speed. However, the shape and dimensions of the object are not directly detectable, and a large surface (e.g. a container) may produce several distinct echoes.

The material of the objects and their orientation have a major influence on the strength of the reflection (measured RCS). In general, reflections from metallic surfaces are stronger than from other materials, e.g., plastic, wood, and people. Typical RCS values are defined in square metres: i.e. 10m2 for a vehicle, 1m2 for a bicycle, and 0.1m2 for a person. Metal objects (e.g., vehicles) are detected at long ranges with high accuracy and confidence.

Safety-certified radar sensors for people detection are available on the market up to a safety Performance Level of PL d. However, the range and relative speed of such safety-certified sensors are limited. Furthermore, the orientation of the sensors needs to be carefully considered to avoid false alarms from the ground.

2.3 Camera-based Sensors

Camera sensors are widely used to detect people from videos and images. Earlier, low accuracy and false alarms were common issues. Deep learning (AI) has greatly improved results; however, the accuracy and confidence levels achieved do not meet typical safety-level requirements.

Stereo cameras offer greater reliability and broader applications by providing a 3D point cloud (distance to the object) combined with camera image data. Modern hardware, supported by parallel processing units, enables real-time frame rates of, e.g., 15 frames per second.

A 3D ToF (Time-of-Flight) sensor emits infrared light within a given field of view, which is reflected by objects in its surroundings. Object distance is determined either by directly measuring the time-of-flight, i.e. the runtime of short emitted light pulses ("pulsed 3D ToF"), or by measuring the phase shift between the emitted and the reflected light of a continuously emitted amplitude-modulated light wave ("phase shift-based 3D ToF"). Measurement data for all pixels are available in a single laser shot. Typical scan frequencies are 10 – 50 Hz.

Fig 10: An Example of a Radar Scan (40 ft container)

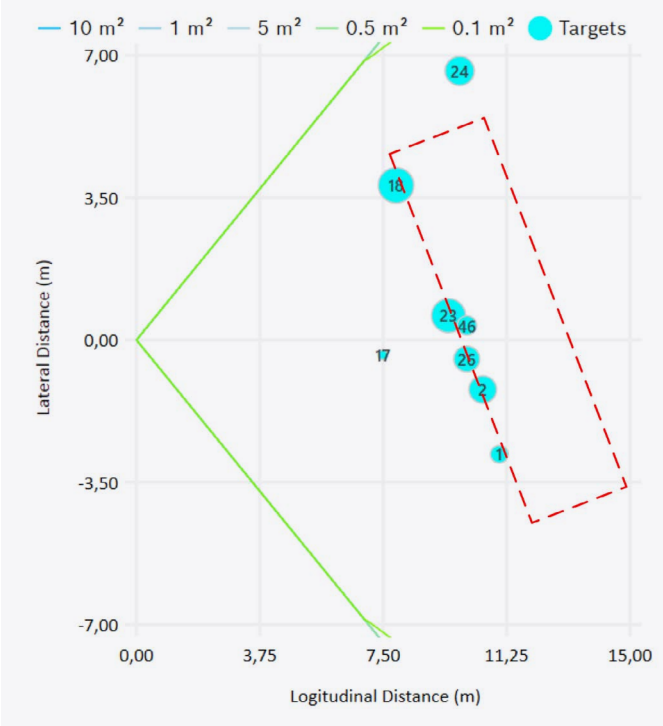


Fig 11: Combination of a Camera Image and 3D ToF Camera Data



2.4 Position Detection Sensors

Position detection is a cornerstone of today's automated vehicles, robotics, and asset tracking systems. Advances in sensor technology enable accurate location tracking in both outdoor and indoor environments.

Position detection sensors can roughly be divided into the following types:

- Radio and radar- based positioning
- Optical positioning
- Inertial positioning and odometry

Radio positioning can be based on satellites (e.g. GNSS) or transmitter beacons located on masts or transponders embedded in the ground surface.

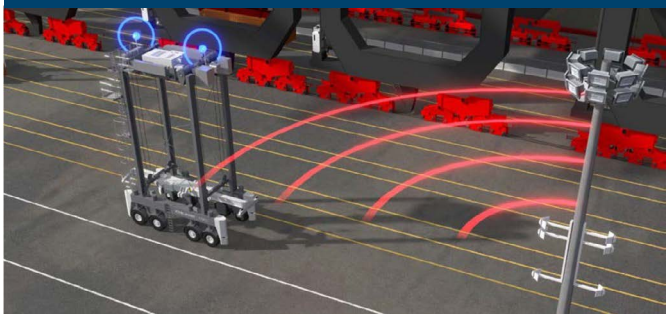
Global Navigation Satellite Systems (GNSS), such as GPS, Galileo, and others, provide worldwide positioning with standard accuracy of around 1–3 metres. For applications demanding higher precision—such as autonomous vehicles, drones, or surveying—GNSS is enhanced with Real-Time Kinematic (RTK) correction. RTK uses reference ground stations (Base Stations) that broadcast real-time error-correction data to moving assets, improving positional accuracy to the centimetre level.

Satellite positioning and beacons on masts require line of sight, which may be difficult to maintain for smaller vehicles.

When GNSS is unreliable or unavailable, such as inside buildings or in underground facilities, UWB (Ultra-Wideband) radio technology can be used. UWB systems use a network of fixed anchors and mobile tags to triangulate positions with an accuracy of 10–30 centimetres. Unlike traditional RFID, UWB is highly resistant to multipath effects and interference, improving location tracking even in cluttered or metal-rich environments. The main requirement is installing the necessary infrastructure, i.e. anchors at fixed, known positions throughout the monitored area.

Radar positioning technology has been used, for example, with reflectors mounted on masts. A new technology is "Ground Penetrating Radar", which looks for a ground radar "fingerprint" and does not require the installation of additional beacons in/on the ground.

Fig 12: Transmitter Radio Beacons on Mast



RFID technology is a form of short-distance (up to 10 metres) positioning and identification.

Optical positioning can be based on rotating laser technology that scans special reflectors at known locations, or alternatively on mapping its environment using SLAM (Simultaneous Localisation and Mapping) algorithms. Camera-based technologies that observe special landmarks have also been trialled.

Inertial Measurement Units (IMUs) combine accelerometers, gyroscopes, and sometimes magnetometers. They provide real-time estimates of motion and position through dead reckoning. While IMUs are not standalone solutions (their accuracy drifts over time), they are valuable for bridging periods when GNSS or UWB signals are unavailable, such as in tunnels, in GPS shadows, or amid signal interference. Combined with external references, IMUs greatly improve system reliability and continuity.

Sensor Fusion

To maximise accuracy and robustness, positioning solutions may utilise data from a variety of sensors (sensor Fusion). Advanced algorithms and Simultaneous Localisation and Mapping (SLAM), synthesise data to produce a single, error-mitigated position output. Multi-sensor positioning architectures enable autonomous vehicles to transition seamlessly between outdoor and indoor logistics hubs and warehouses while tracking assets with high precision.

3. Solutions

The solutions can be divided into those for a) horizontally moving equipment and b) the transfer zones where the container is handed over, i.e. the interchange areas.

3.1. Horizontal Transport

The horizontal transport system serves the stacking yard cranes and comprises two separate logistic operations:

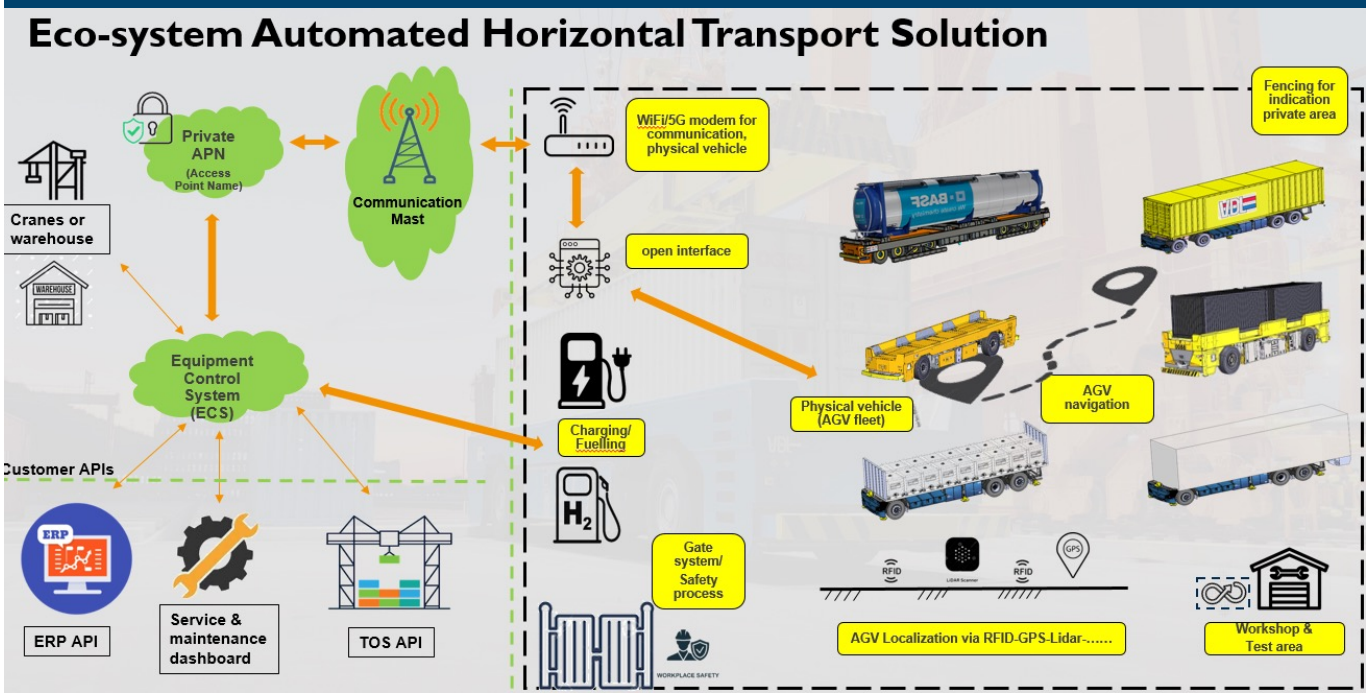
- **Landside transport:** moving containers from the terminal truck gate or intermodal railhead to the stacking cranes and vice versa. Landside transport is typically handled by external road trucks.
- **Waterside transport:** moving containers from quay cranes to stacking cranes and vice versa. Waterside transport can be highly automated using AGVs, automated straddle carriers, and similar systems.

In a mixed-mode port layout, these logistic loops may cross or share common pathways.

3.1.1. Lay-out, Common Pathways and Traffic Control

Traffic control for a fleet of purely unmanned horizontal transport vehicles is relatively predictable, as the vehicles are equipped with accurate positioning systems and obey commands with robotic precision. Road trucks entering the terminal, by contrast, are driven by external, unfamiliar personnel and introduce a random element into traffic control. External truck drivers need clear instructions on where to go and how to interact when encountering unmanned vehicles at intersections or on shared pathways. Traffic control is obviously simpler for the so-called 'end-loaded' stacking crane layouts, since the external trucks only drive to the landside end of the stacks and the waterside/container yard is generally separated. With sideloading stacking cranes, external trucks drive under the cranes (RTG) or cantilevers (RMG) and regularly encounter unmanned vehicles. In such cases, the following priority rules could be implemented:

Fig 13: Example of Eco-system of an AGV Operation



Priority Rules

- Unmanned vehicles (including stacking cranes) must give way to road trucks. In risk assessment scenarios, an external truck driver may potentially cause a collision, but the unmanned vehicle should be stationary at that moment.
- Road trucks must not be obstructed by unmanned vehicles. Two-way traffic lanes should be avoided ("deadlock" resolution is difficult).
- STS cranes and stacking cranes have priority over unmanned horizontal transport.
- Emergency vehicles to be managed.

Management of environment modification and coactivity:

- Construction and road works zones.
- Blocking situation caused by another machine or piece of equipment.

Road Trucks

Road trucks are probably the most difficult piece of equipment to manage in mixed-mode automation, since they are not the property of the terminal operator and thus are not inherently equipped with any positioning devices or sensors. Knowledge of road truck positions would help with general traffic planning. This could be implemented either by a temporarily installed on-board navigation instrument (GNSS) or by positioning based on external means, such as a camera-based surveillance system.

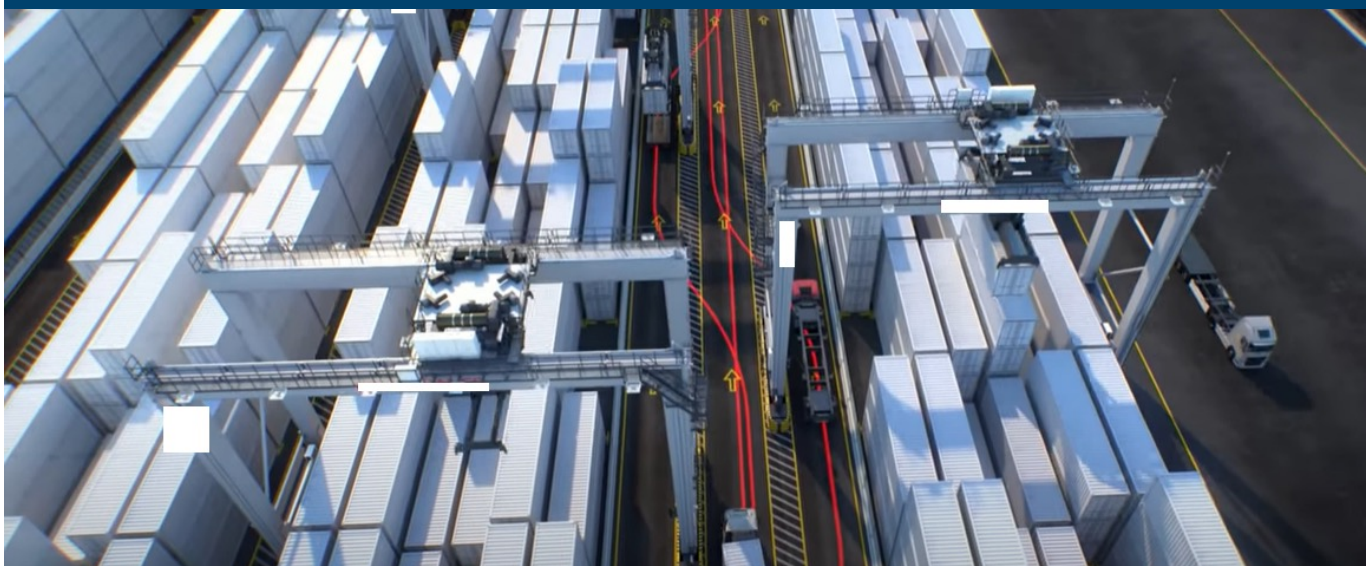
The drivers of the road trucks are not trained by the port operator, so the instructions they receive when entering the port must be very simple and clear. Because their movement cannot be controlled as precisely as AGVs, their potentially unpredictable behaviour could complicate the traffic control system.

Side-loaded Gantry Crane Lay-out

Automated side-loaded gantry cranes (Cantilever ARMGs, ARTGs) are mixed-mode automation systems in which unmanned stacking cranes share the operating area with manned road trucks.

This contrasts with automatic stacking cranes (ASC), which have a specialised end-loaded layout in which the road trucks do not enter the stacking area. Automated cantilever gantry cranes and RTGs, on the other hand, utilise the traditional side-loaded layout, in which the trucks drive along the side of the container stacks and under the stacking crane (***figure 14***). The trucks' driving lanes may be fenced to prevent them from entering the stacking crane's drive path. Some installations also provide separate fenced driving lanes for road trucks and AGVs (e.g. Tobishima Container Berth, Nagoya). However, mixed-mode automation targets more flexible solutions without rigid fencing. For example, bypass lanes can be introduced to allow the trucks (and AGVs) to pass each other. In this case, the trucks may cross the stacking cranes' travel paths, necessitating collision-avoidance solutions.

Fig 14: Person Detection in the Driving Path of the Machine



3.1.2. Collision Avoidance for Horizontal Transport

See also PEMA Paper Ref; IP30 People detection in Ports and Terminals

Collision avoidance between vehicles, especially between a vehicle and a pedestrian, is the key safety issue in mixed-mode automation. Pedestrians are generally not permitted in an automated terminal, but in practice a truck driver can physically exit his cab (unless locked inside), and this scenario needs to be taken into account in the Risk Assessment process.

Sensors described in Chapter 2 may be used for collision avoidance (object detection), provided they meet the required safety Performance Level (PL r). In general, detecting a road truck is easier because of its size and material (metal). It may be considered that the driver is better protected in the cabin than a pedestrian (reduced PL r). It should be noted that potential collisions between two vehicles caused by the truck driver cannot be completely eliminated.

3.1.3. Example: Laser-based Gantry Collision Prevention 3D

This solution is designed to detect 3-dimensional people and objects in the path of the machine (RTG, RMG, and STS crane) and stop the machine if any are detected.

The sensors are placed along the outer edge of the bogie (in total, 4 scanners/machines per bogie, 2 per edge). The sensors create a 3-dimensional field of view. Within this field of view, zones are set for pre-detection (blue), warning (yellow) and alarm (red). See ***figure 15*** below. The functionality is as follows:

1. The 3D monitoring area is defined in front of the bogie. The field of view is ahead of the direction of travel at a desired height above the ground and covers the width of the bogie plus a safety margin.

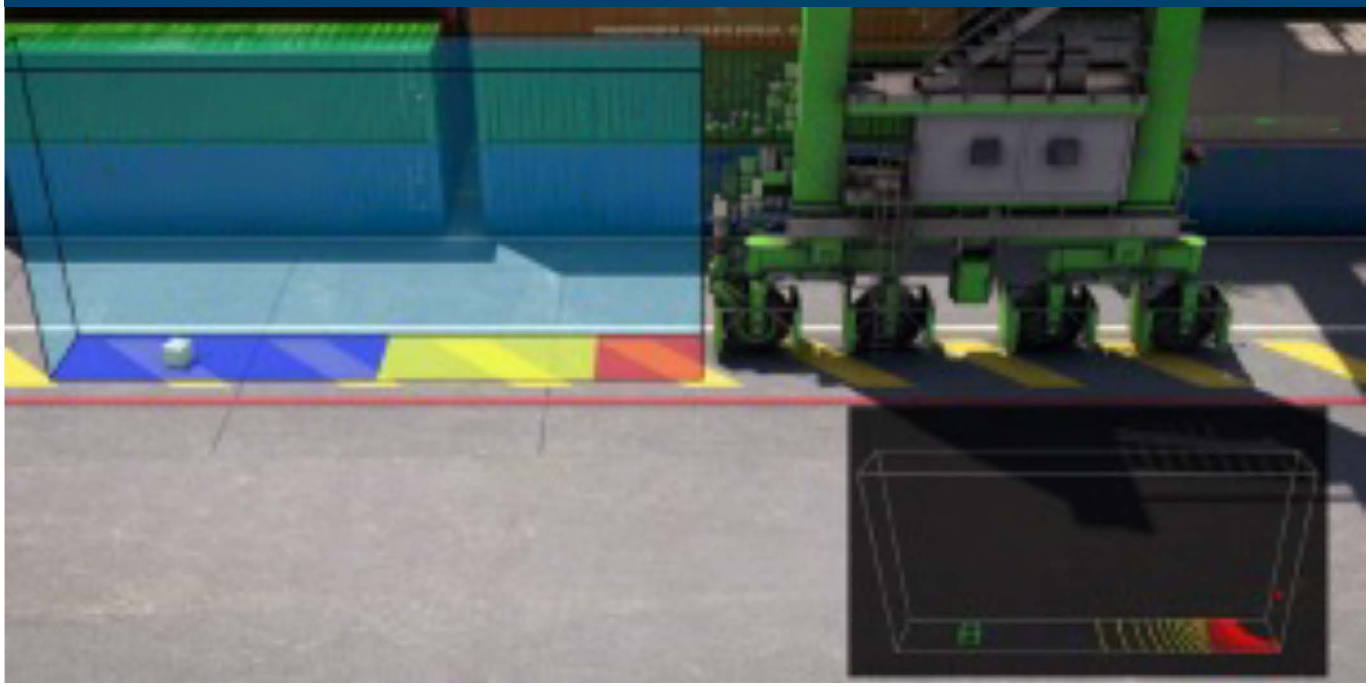
2. If an object or person is in the monitored zone, the system detects this and generates a warning or alarm.

3. The information is transmitted to the crane's PLC.

4. The crane PLC will slow the movement or stop the machine.

Note: For the functional safety requirements of such equipment, please see chapter 4.

Fig 15: Person Detection in the Driving Path of the Machine



3.1.4. Example: People Detection at Railyard Crane Operation

This solution assists the crane operator by using a 3D Camera to detect people and objects in defined areas of the rail crane and to support the operation when visibility is obscured.

- 3D Cameras installed on the crane structure (each leg of the crane at approx. 8 m height).
- 3D spatial areas of interest are defined (***figure 16***, yellow and blue areas). Up to 16 spatial areas, e.g. one per each track and aisle, is possible.
- Several spatial areas per track and aisle can be defined, optionally split into near field (stopping field) and far field (warning field).
- Information about person detection can be transmitted either by the infringed field and/or by X-Y-Z coordinates. Using this data, the crane can continue operating by adjusting its planned route.
- The camera detects persons entering the field (AI) and generates the following:

– **Object list:** Detailed information is transmitted to the crane, including as object class (person) and X-Y-Z coordinates.

– **Field infringement:** Alternatively, information about a field infringement by an object or person can be provided.

Based on this transmitted information, warning and stop signals, as well as 2D RGB visualisation images, can be used to influence the operation.

Duplicating this system on the opposite side of the crane leg can further improve the safety and reliability of person detection.

Fig 17: 2D RGB Image and 3D Point Cloud

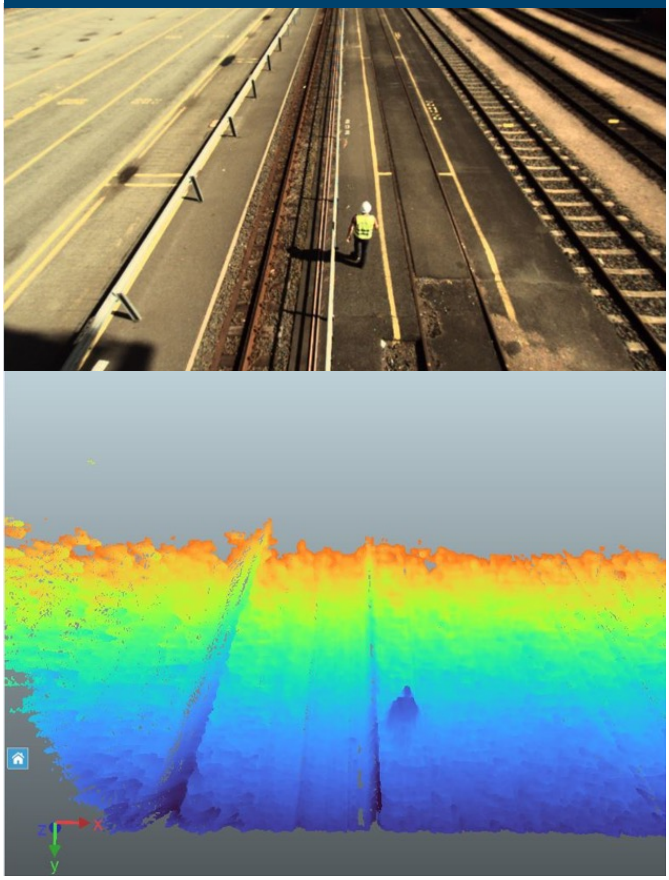
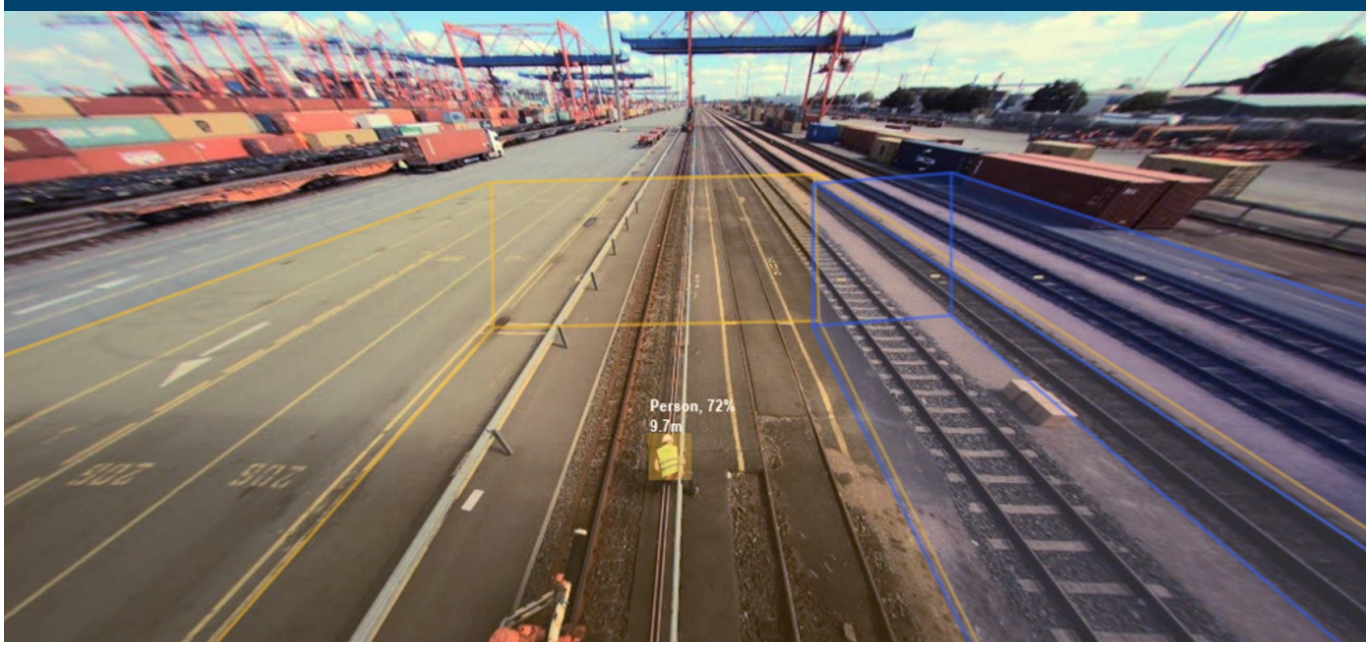


Fig 16: Left Warning Field Infringed by Person (yellow), Right Warning Field Free (blue)



3.2. Interchange Areas

Interchange areas are locations where a container is transferred from one vehicle or crane to another. A typical example is a road truck, which is loaded or unloaded by a crane. The horizontal transport vehicle may be manned (e.g., a road truck, terminal tractor, or straddle carrier), while the crane may be unmanned, in which case we have a mixed-mode automation situation.

In mixed-mode interchange areas, road truck loading and unloading operations are either remotely operated or fully automated, depending on the stack layout. In fully automated operations, a measurement system is used to determine the truck's profile and location, as well as the container positions. A camera or laser imaging system is used for fine positioning when placing the container onto the truck.

3.2.1. End-loaded Stacks

In the case of end-loaded stacks, the interchange areas are located at the perimeter of the automated zone. Fully automated truck handling in end-loaded ASC stacks typically requires the truck driver to leave the interchange area and confirm the automatic operation at a kiosk.

3.2.2. Side-loaded Stacks

In side-loaded stacks, containers are transferred between a manned truck and ARTGs (Automatic RTGs) or ACRMGs (Automatic Cantilever RMGs), or vice versa. In this type of operation, the manned truck travels within the stack area, and it is generally considered that the truck driver should not leave the cab, as this would create a pedestrian hazard. To fully automate truck loading and unloading in side-loaded stacks, a reliable pedestrian detection and warning system must be provided.

3.2.3. Straddle Carriers

In an automated straddle carrier terminal, all facilities requiring mixed auto/manual operation are recommended to be sited at the perimeter of the automated zone or relocated there. This will ensure that the automated area has a practical shape for efficient operation and will guarantee smooth access for people to the area without disturbing other operations inside the terminal area.

Particular attention needs to be devoted to the establishment of safety procedures and access control in areas with such mixed auto/manual operations, such as:

- Waterside interface
- Truck and rail handovers
- Maintenance areas
- Refueling
- Empty container interchange
- Handling of reefers.

An example of fully automated truck handling in an automated straddle carrier terminal is shown in ***figure 18, next page***. The truck driver must leave the interchange area and confirm the automated operation at a kiosk.

Fig 18: Fully automated truck handling



3.2.4. Example: Laser-Based Area Surveillance Truck Operation Solution Under an RTG

In this solution, it is necessary to detect people within the crane's working area. In particular, the transfer from a manually driven truck to an automated RTG and RMG crane should be carried out safely and without injury. The detection system for this example, a truck lane under an RTG, is based on two multi-layer lasers, each with a 22.5° horizontal field of view and 64 scanning planes.

The laser scanners are mounted under the gantry beams and face downwards. The sensors are mounted at 90° so that the 360° scan plane is vertical. One scanner covers the side facing the yard and the front of the truck, and another monitors the side facing the chassis and the rear of the trailer.

The system functions as follows:

1. A 3D monitoring area is defined. The width of the lane is monitored and extends along the yard and up to the gantry. The RTG's travel range to the front and rear is approximately 10m beyond the RTG's physical limits.

2. Now a truck with trailer (with or without container) enters the transfer area under the RTG.

3. The truck and trailer are permitted objects that do not trigger an alarm.

4. If the truck driver leaves the cabin or a person enters the monitored area from outside, the system detects this, sends a stop signal to the crane control system, and prevents the load from being lifted or lowered into the monitored area.

Process Flow:

Red – RTG Operation in the area is not permitted

Green – RTG Operation in the area is permitted

1. Area is empty (status: green)
2. Truck arriving (status: red)
3. Truck at delivery position (status: green)
4. Driver leaving cab (status: red)
5. Driver re-enters area from outside (status: red)
6. Driver is outside the area (status: green)

Fig 19: Zones in Different Stages

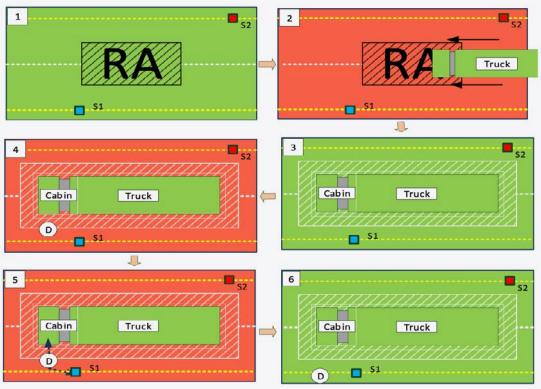


Fig 20: 3D-Scan with Surveillance Area

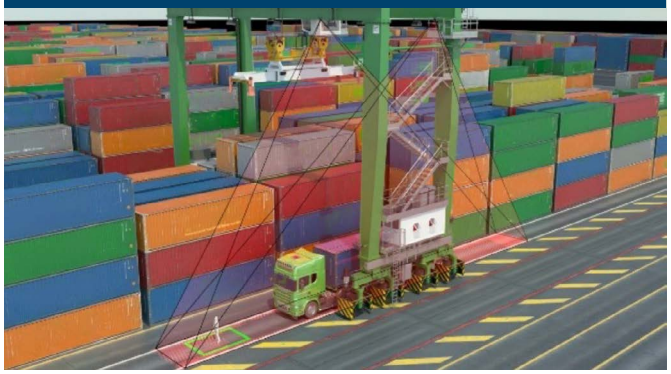


Fig 21: Mounting Positions on a RTG



Fig 22: Mounting Positions on a RTG

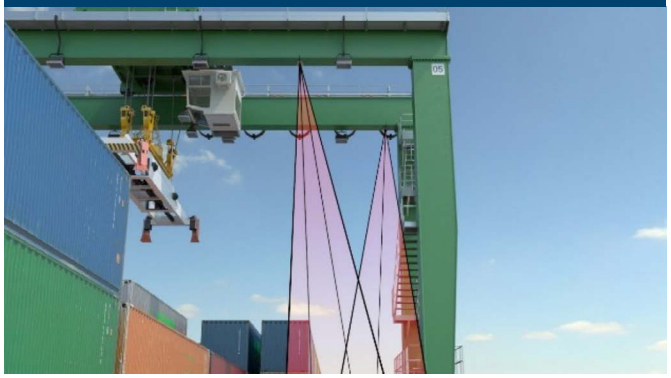


Fig 23: Person Beside the Truck, Detected by the Measurement System (square around the person in the laser scanner raw data on the left side)



- 3D point cloud raw data (left), image of scene (right), with person beside the truck/trailer (red circle).
- Systems on the market are safety-certified according to EN ISO 13849-1 - 2.
- The system also checks the position of the cabin to ensure that the load cannot be dropped onto it.
- Throughout the process, the truck's movement is monitored.

4. Risk Assessment and Safety Standards

4.1. Introduction

When undertaking a risk assessment of an autonomous vehicle/crane project, the likelihood of global risks must be assessed not only in relation to operating the vehicle at the intended location or along the intended route, but also across all phases of the product life cycle. This includes the product development phase (the safety of the product itself), the integration and deployment phase, and the final handover and operation phase.

Therefore, it is necessary to ensure that all stakeholders, including the product's manufacturer, integrator and user/owner, **demonstrate the overall safety methodology and risk analysis**, and show how risks are mitigated, by compliance with a referenced framework of industry standards or other means.

Global risk analysis will encompass risks to humans (collision with pedestrians or workers) as well as risks of damage to infrastructure, equipment, vehicles or machines.

Context and framework for Safe Autonomous Vehicle/ Crane Deployment

The **Safety Assessment** and **Risk Management Plan Activity** should be developed in accordance with the following 2 headings:

1. **The generic specifications of the product itself.** This includes all information about the intended use of the autonomous machine, defining the design limits within which the machine can operate safely at a defined automation level. This can also be referred to as the Operational Design Domain (or ODD) for which the autonomous machine is designed.

2. **The specific requirements** for the planned project and the intended operation site.

These requirements shall cover, but are not limited to, the operational concept, the environment, specific constraints, interactions with other systems and parties, environmental conditions at the intended site, descriptions of the driving routes, etc.

The risk management plan must primarily cover Safety, which relates to the prevention of accidents (involving people or otherwise). The plan must also include Functional Safety (relying on an active system) and System Security, which relates to the prevention of malicious activities (intentional or otherwise) (Ref PEMA paper IP 30 Cybersecurity in Ports and Terminals).

Functional Safety is defined as the absence of unreasonable risk arising from hazards caused by malfunctions of Electrical and/or Electronic (E/E) systems.

The objective is to identify all risks and categorise them by criticality.

For each unacceptable risk, a mitigation measure shall be developed. The mitigation measures can be implemented through management processes, additional design features and monitoring, but mainly through the introduction of safety functions.

This risk management plan shall be developed in accordance with a framework of standards and norms. This list of standards shall be defined in accordance with the applicable legislation of the manufacturer's country, the legislation of the intended country of use, and the international legislation related to autonomous machinery. Other relevant legislation, depending on the vehicle/crane type, its intended use, and all relevant state-of-the-art standards for autonomous technologies and autonomous trucks (e.g., for use in a private area or on open roads), should also be considered.

For example, in addition to any local legislation applicable to the vehicle manufacturer and the intended country of operation, the following framework of standards may be applied to the use of an autonomous vehicle in private areas to comply with 2006/42/EC:

- **ISO 9001:2015** – Quality Management System
- **SAE J3016** – Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicle
- **ISO 12100:2010** – Safety of machinery – General principles for design – Risk assessment and risk reduction
- **ISO 13849-1** – Safety of machinery – Safety-related parts of control systems
- **IEC TS 62998-1** – Safety of machinery – Safety-related sensors used for the protection of persons
- **IEC TS 62998-3** – Safety of machinery – Part 3: Sensor technologies and algorithms
- **ISO 3691-4** – Industrial trucks – Safety requirements and verification
- **SAE J3061** – Cybersecurity Guidebook for Cyber-Physical Vehicle Systems
- **Additional standards:**

– **ISO 26262** – Road vehicles - Functional safety

– **ISO/PAS 21448** – Road vehicles – Safety of the intended functionality (SOTIF)

– **ISO 21434** – Road vehicles – Cybersecurity engineering

– **NF EN 62061** – Safety of machinery – Functional safety of electrical, electronic and programmable electronic control systems

The **safety requirements** are then applied to the 3 main phases in the deployment of an Autonomous Fleet:

Product Safety, i.e. Vehicle Safety, aims to ensure overall safety of the autonomous machine in the context of a generic intended use (ODD);

Deployment Safety aims to identify every risk associated with a site's specific characteristics and to define the additional external measures to be implemented to mitigate all identified risks to an acceptable level.

Operational Safety aims to ensure the definition and implementation of operational procedures consistent with all safety requirements identified in the 2 previous activities.

4.2. Methodology Framework

The risk management activity should be **system-oriented** and **comprehensive**.

System-oriented means it should not be limited to the vehicle alone but should extend to the overall **Automated Transport Systems** (ATS), in which **Automated Vehicles** (AVs) are subsystems. The vehicles themselves consist of subsystems and components that the risk management plan must also address.

Comprehensive means that Risk Management must be considered from the earliest stages of design through to the last day of operation, thereby covering the entire life cycle of every project.

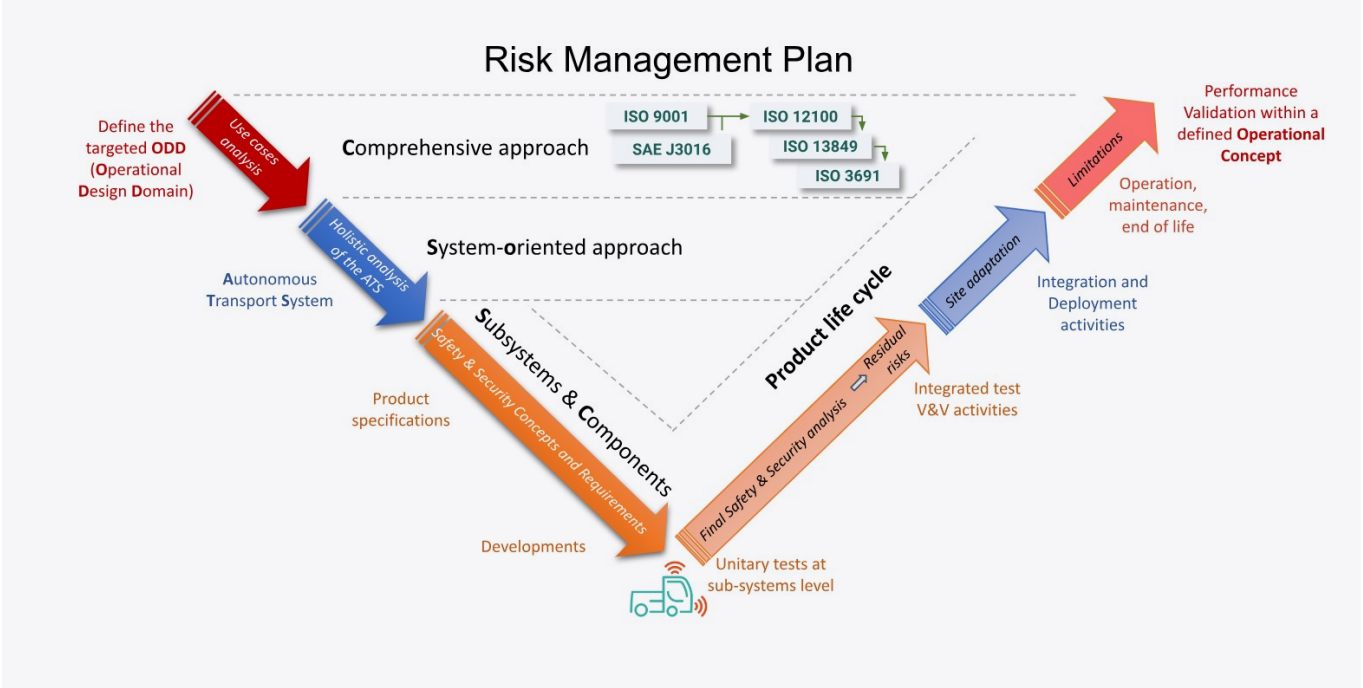
Based on the above, an example of a global **Risk Management Plan** is illustrated in ***figure 24***.

In accordance with ISO12100, every situation and use case for the targeted ODD shall be analysed using a top-down (deductive) approach to identify potential risks. If the risk is unacceptable, a mitigation measure must be implemented to address the potential root cause(s) or to limit exposure (situation) or consequences (impact), thereby reducing the risk to an acceptable level.

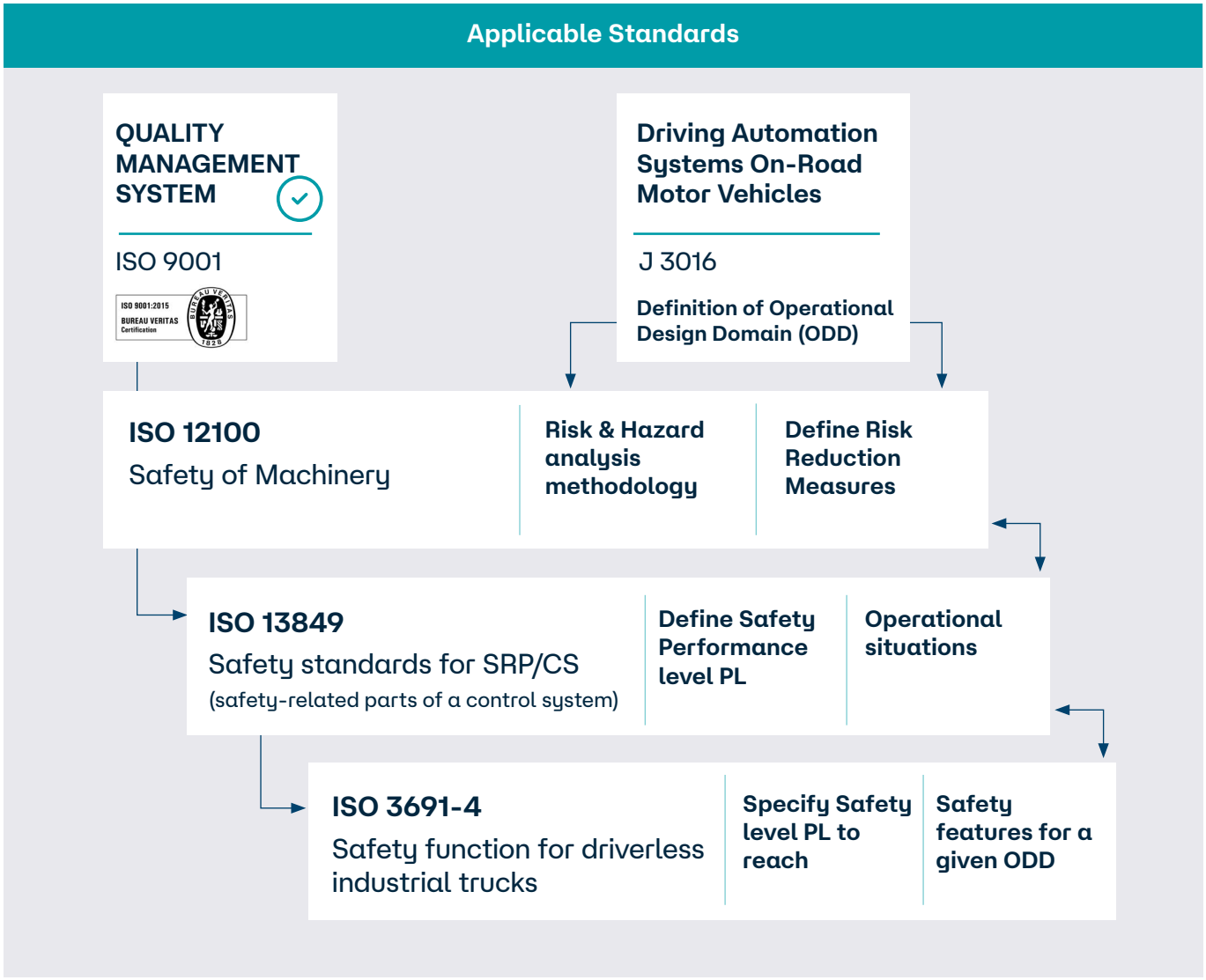
If the mitigation is achieved through an embedded electronic or electrical function (e.g. anti-collision), then, in addition to the expected functional performance, this function shall meet the required integrity level (Performance Level – PL in the machinery standards) as defined in ISO 13849. To support product development and Safety-related activities (without replacing the risk analysis), the ISO 3691-4 standard can be used, depending on the intended application.

In addition to the Performance Level, so-called "**performance classes**" are defined in the IEC TS 62998-1 and -3 standards. These standards specifically address the probability of target/ object detection and the capability to detect defined remissions (surfaces). The "performance class" (detection capability) can be understood as equivalent to the Performance Level (systematic capability). For example, a Performance Level d system must also meet the requirements of performance class D. In the context of personal safety (collision avoidance), the requirement could be the capability to detect a 6% remission for a whole body with a coverage probability of > 1 - 2,5 x107.

Fig 24: Risk Management Plan



The hierarchy of the various international standards can be illustrated as follows:



The integrity level required for each safety function or feature shall be determined by the severity and frequency of the identified risk.

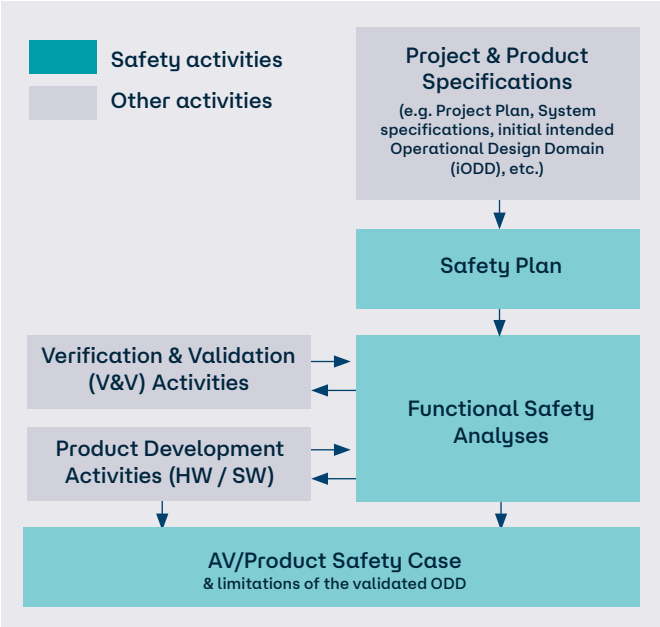
For example, in situations involving mixed traffic with other vehicles and coactivity with pedestrians, the following integrity level could be applied depending on national regulations and legislation:

Autonomous Vehicle Design	
Use cases (ODD)	**Safety level reached**
Emergency Braking	PLd
Obstacle Avoidance	PLd
Lateral Deviation Monitoring	PLd

* Note: Safety level may differ depending on the specific site risk analysis, - hazard risk frequency and controllability may impact the performance level integrity required.

4.3 Autonomous Vehicle/Crane Development Phase – Safety Methodology

This section will describe the safety methodology requirements to be implemented during the AV development phase.



For each development project, a **Safety Management Plan** shall be developed, under the responsibility of the **Safety Manager**, that defines all safety-related activities.

A **Functional Safety Analysis** shall follow must include the following steps:

1. Identify hazards and Functional Hazardous Events (FHE) through a Hazard Analysis & Risk Assessment (HARA) based on the system specifications and the initial intended ODD, and specify the safety goals;

2. Mitigate risks by appropriately identifying and defining design mitigation measures:

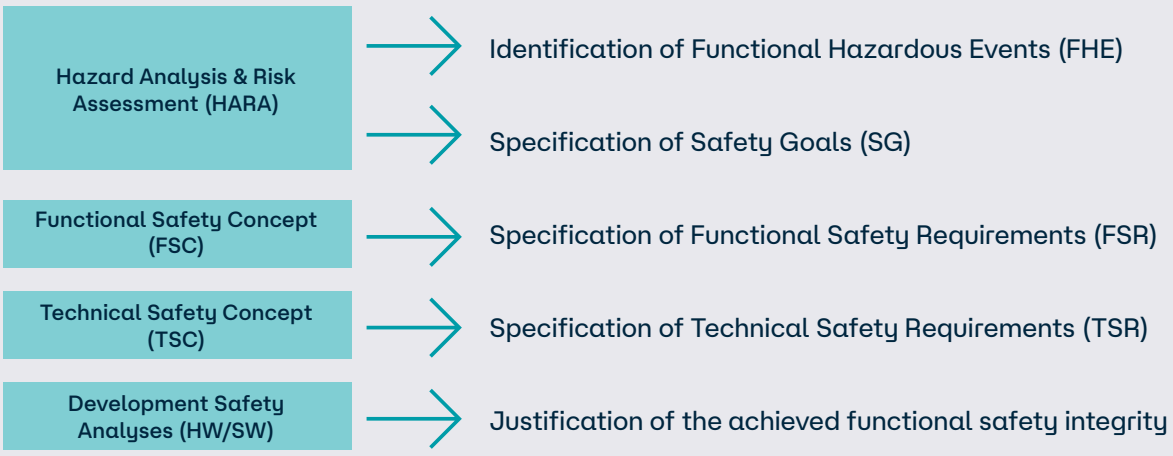
a. Functional Safety Concept (FSC): the specification of the **Functional Safety Requirements (FSR)**;

b. Technical Safety Concept (TSC): the specification of the **Technical Safety Requirements (TSR)**;

3. Demonstrate that the required **safety goals** are achieved because of the appropriate **Development Safety Analyses** at hardware and software levels;

4. Compile the results into a Safety Case report and highlight the limitations of use within the initial intended ODD to define the residual risks and issue a validated ODD.

Functional Safety Analyses



Development Safety Analyses - Hardware

The development safety analyses at the hardware level are implemented to assess:

- The hardware architectural metrics;
- The safety goal violations resulting from random hardware failures.

The following tools and methods can be used to demonstrate that safety requirements can be met: reliability prediction, Failure Mode and Effect Analysis (FMEA), Failure Mode and Effect Summary (FMES), and Fault Tree Analysis (FTA).

Development Safety Analyses - Software

The product manufacturer shall conduct software safety analyses at the architectural level to identify potential design gaps in the software.

This software analysis shall include the following activities:

- Software coding rules review
- Software failure mode coverage analysis
- Dependent failure analysis/freedom from interference analysis.

Development Safety Analyses – V&V Phase

A **Verification & Validation** plan shall be submitted and shall comply with the requirements of the relevant quality standards.

The aim of the **Verification activities** is to demonstrate that all requirements for each phase of the development cycle comply with the initial safety plan.

The aim of the **Validation activities** is to demonstrate that the developed product complies with the Safety requirements for the intended use and ODD.

Development Safety Analyses – Safety Case

A Safety Case Report shall be prepared to ensure traceability and to log and synthesise the safety demonstration. A Safety Case is a structured argument, supported by evidence, intended to justify that a system is acceptably safe for a specific application in a specific operating environment.

To do so, the **AV Safety Case Report** comprises all the work products and documentation for the safety-oriented development scope, with references/ links to the relevant results of other activities (e.g. development, V&V, etc.).

The output of the **Safety Case Report** highlights the limitations of using the initial intended ODD to define residual risks and to allow a validated ODD to be issued.

Autonomous Vehicle/ Crane Deployment Phase

This first phase of deployment activities shall consist of a comprehensive site analysis conducted through a Site Assessment Report (SAR).

This site analysis shall include the following activities:

- Site and route description and characteristics
- Environment description
- Environmental condition of the site
- Detailed scope of operation and operational constraints and requirements
- Interfaces and process with other (units of) equipment
- Operational concept and interaction with resources
- Control and monitoring concept
- Integration architecture.

This analysis allows for the identification of all risks and aggravating factors associated with the site's characteristics according to the validated ODD, and the specification of mitigation measures to reduce all identified risks to an acceptable level.

This analysis and the mitigation measures shall be validated by all the project stakeholders (AV manufacturer, system integrator, site owner, operations-accountable personnel).

These mitigation measures shall then be implemented, and a periodic review shall be organised to ensure compliance with the conclusions of the site assessment report.

If a risk remains outside the validated ODD limits, a dedicated committee (The Project Risk Committee) shall be established to define any resulting residual risk and determine which party will be accountable for it.

This committee shall be composed of personnel with accountable roles within the organisation of the vehicle manufacturer such as:

- The Safety Manager (or its representative)
- The Product Director (or its representative)
- The Project Team.

Each decision shall be shared with the other stakeholders such as the site owner and the accountable operations person. When the site is ready and compliant with the **SAR** conclusions, the deployment of the autonomous machine can commence under the responsibility of the s**ystem integrator.**

The system integrator shall demonstrate the correct behaviour of the autonomous machine with a **Validation Phase.**

This **Validation Phase** may require an **onboard supervisor/operator** inside the vehicle to assess specific situations. A formal agreement with the stakeholders involved should be drafted before authorising the **Driverless Operation.**

The system integrator is responsible for providing all the necessary **training** and **awareness** sessions to the resources involved in the on-site operation and maintenance of the autonomous machine.

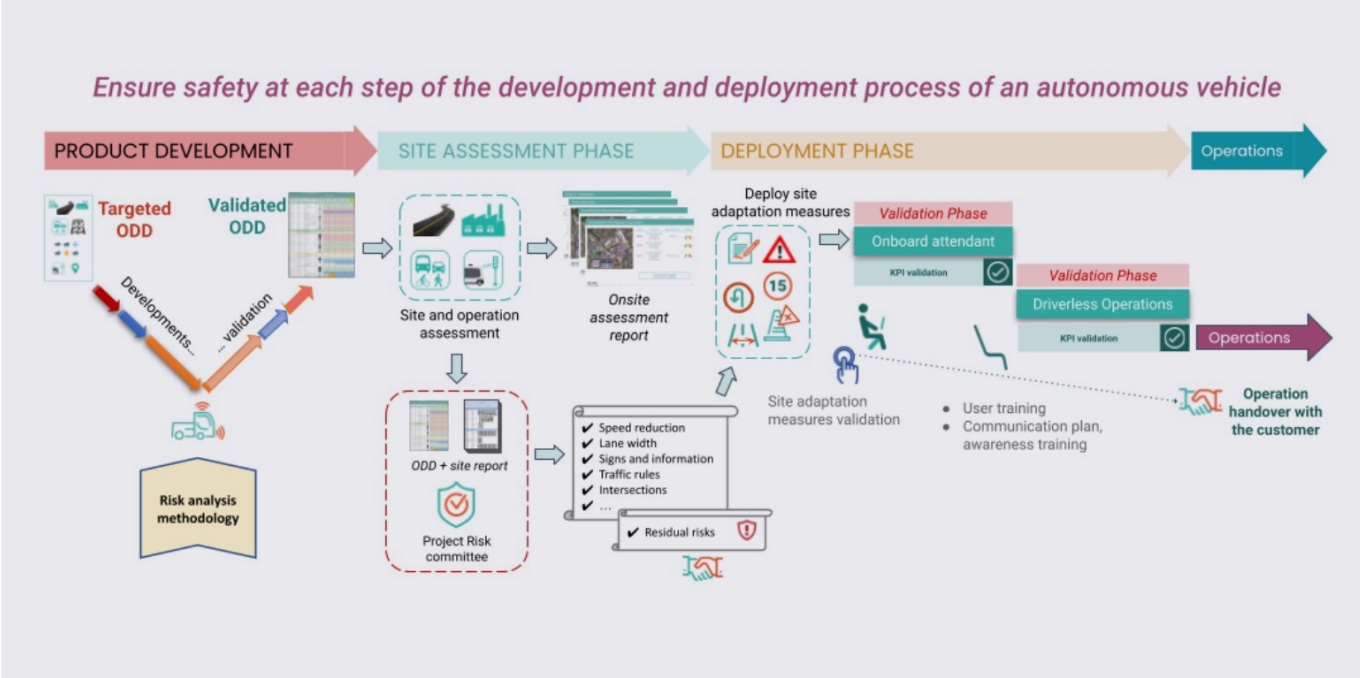
The **Validation Phase** can be incremental in order to reach the full operation scope and shall remain under the responsibility and supervision of the **system integrator** until a final handover is organised.

Autonomous vehicle/ crane Operation phase

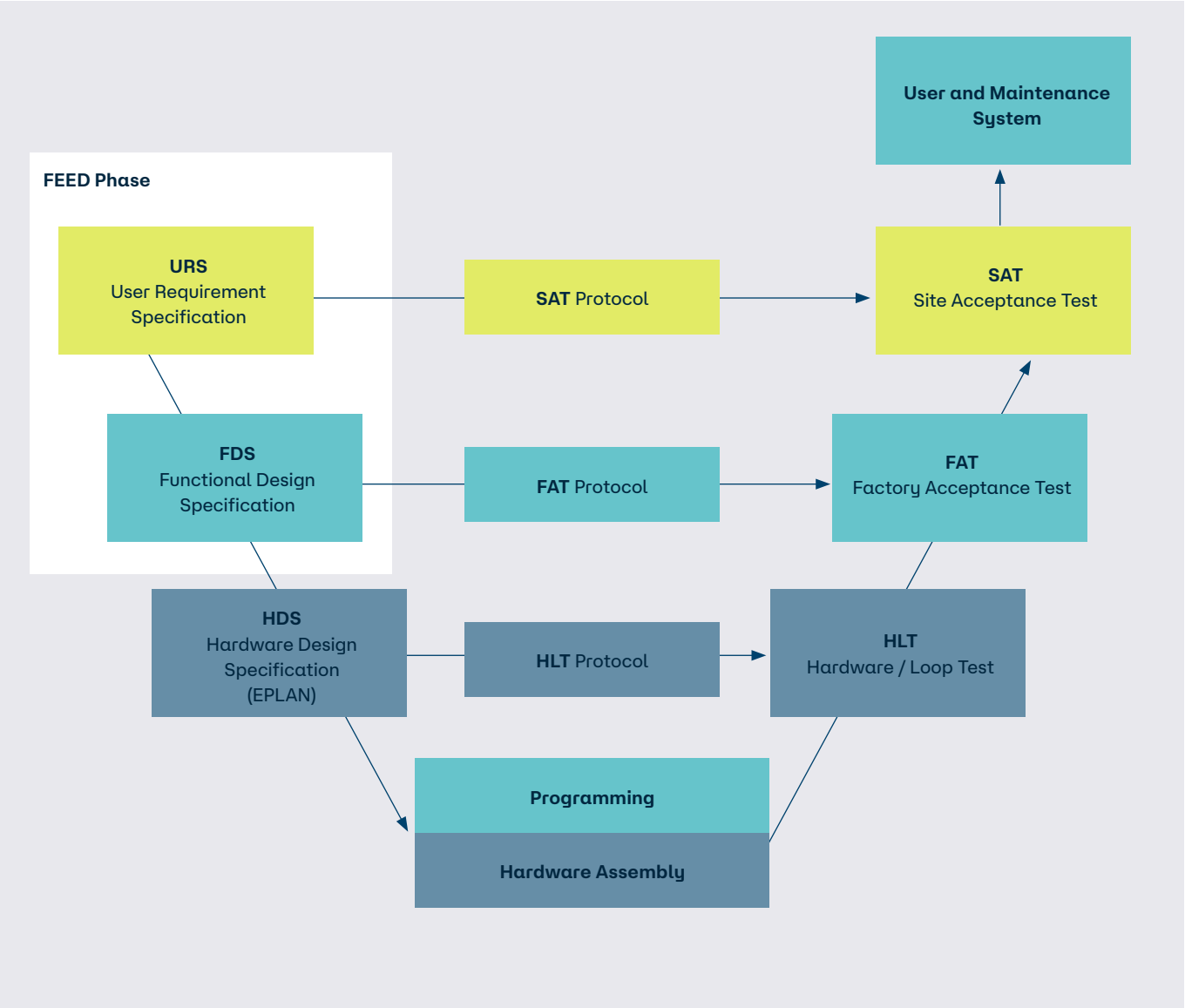
At the end of the Validation Phase, a formal agreement should be drafted among all stakeholders before starting the Handover Gate phase, which transfers responsibility from the system integrator to the responsible end-user operations team.

This final review shall cover the following key points:

- Review of the **Global Safety Assessment** of the project (Safety plan)
- Review and validation of the mitigation measures and site adaptation
- KPI review of the **Validation Phase** (with onboard attendant and driverless phase)
- Review and validation of the operational concept
- Review of the supervision concept
- Validation of the training and resources involved with the AV.



During the operations phase, any modification to the operational concept, context, or environment should be communicated to all stakeholders to assess the impact of any new risks.



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