Mobile dual arm robotic workers with embedded cognition for hybrid and dynamically reconfigurable manufacturing systems

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Summary:

This demonstrator deliverable is a follow-up to deliverable D2.4 THOMAS safety system – initial prototype. It is a description of the safe collaboration systems developed in THOMAS work package 2 and covers the safety design implemented on the MRP, the end effector safeguarding system on one of the robot arms and the 3D safety camera monitoring hazardous workplaces.

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1. EXECUTIVE SUMMARY

The THOMAS vision of a dynamically reconfigurable shop floor utilizing autonomous, mobile dual arm robots in interaction with human operators will be demonstrated in two pilot cases. The first will be developed at PSA in France, representing the needs of the automotive industry, the second at AERNNOVA in Spain representing the aeronautics sector.

In order to ensure human safety during the operation and interaction of the THOMAS robots and other machines, an iterative process of risk assessment and subsequent risk reduction by suitable risk reduction measures was performed. THOMAS safety had its focus on three main topics: safeguarding the omnidirectional THOMAS mobile robot platform, safeguarding the robot arms mounted on the MRP and safeguarding particularly hazardous shared workspaces.

Safeguarding the THOMAS mobile robot platform. The mobile robot platform (MRP) and its robot arms as the core entity introduced by THOMAS, are given particular scrutiny with regard to its safety requirements. A safety concept has been drafted for the MRP that identified the general requirements for safety functions. A subsequent safety design translates the product-neutral safety concept to concrete safety products. This safety design includes, amongst other safety devices, new generation safety laser scanners that monitor the MRP's environment and decelerate or stop the MRP in case the active safety fields are infringed by a worker and safe wheel and wheel direction encoders so that the safety fields can automatically adjust to the actual motion of the MRP. In combination, these safety systems ensure that the MRP may freely move around in its operating environment without jeopardizing workers.

Safeguarding the MRP robot arms. In addition, the safeguarding of the robot arms and its tools has been investigated. A prototypical demonstrator has been built and installed on the MRP. This end-effector safeguarding technology detects when a worker reaches out to the end-effector and, similar to the safety fields of the laser scanners on the MRP, can trigger the robot arm to slow down or completely stop in order to avoid any accidents.

Safeguarding shared workspaces. Finally, a concept for safeguarding static hazardous workplaces, such as the damper compression machine in the PSA pilot case, using a 3D safety camera currently under development at SICK, is presented. The use of such a 3D safety camera allows the redesign of fenced workspaces to be more open and more accessible by workers, thus increasing efficiency without compromising worker safety.

The following figure summarizes the activities of WP2 as well as the activities in the two related work packages 6 (integration) and 7 (assessment). For the MRP, the implementation of the safety design was directly made in the MRP prototype. In WP6, the safety hardware was integrated into the THOMAS demonstrator and was tested, evaluated and refined in an iterative process. The final assessment of the safety systems will then be made in WP7 towards the end of the project.

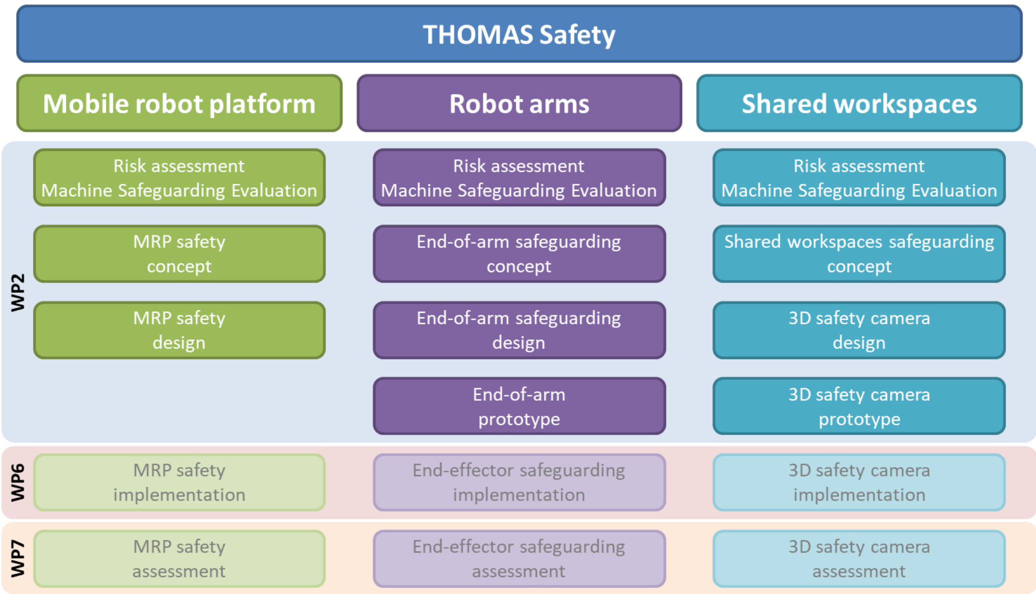

Figure 1: THOMAS Safety concept

2. Introduction

THOMAS investigates the vision of a dynamically reconfigurable shop floor utilizing autonomous platforms. The introduction of mobile dual-arm-robots in the shop floor is described in the project's concept where the robots and the platforms

- navigate freely and in a safe way across the shop floor avoiding humans and obstacles,
- perform tasks on products that are being transported by autonomous robotic units as well,
- position themselves inside workstations and execute tasks using the available tooling,
- are dynamically re-allocated to different tasks without human intervention,
- perceive their environment and adjust their behaviour to collaborate with humans, and
- communicate with each other through a network of services and reason over their course of actions in order to achieve the production goals.

Each one of these features is a challenge in itself. In addition, they all give rise to the question how human safety can be guaranteed in the emerging demonstrators. These questions are covered by WP2 of this project which comprises the development of a safety concept and the investigation of human robot interaction strategies.

Figure 2 below outlines the sequence and interdependence of deliverables over the course of the project. This deliverable is a sequel to D2.4 and describes the safe collaboration systems developed to safeguard the THOMAS open production station.

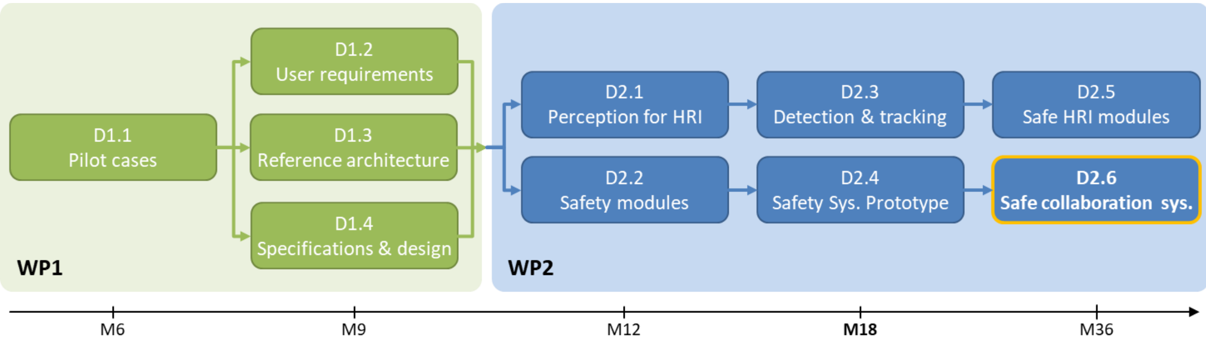

Figure 2: Overview of related deliverables

Chapter 3 summarizes the safety design, the safety hardware as well as the implementation and configuration of the safety systems deployed on the THOMAS MRP.

Subsequently, **Chapter 4** illustrates the end-effector safeguarding technology developed in WP2 in order to safeguard the robot arms on top of the MRP.

Finally, **Chapter 5** explains the 3D safety camera technology and the software developed for the marked-based detection of the MRP.

In conclusion, **Chapter 6** summarizes work performed in WP2 and provides an outlook on further steps with regard to safety within the framework of the THOMAS project.

3. MRP SAFETY

In order to reduce the risks related to the operation of the system, the machine is equipped with a complex safety control system, comprising safety controllers, safe position sensors for monitoring the position of moving parts (robot and torso), safety encoders for monitoring the movement and orientation of the wheels and safety laser scanners for monitoring the area around the machine.

3.1. Identified Risks

Risk identified – Impact due to movements of the robot arms and the torso.
The robot arms are certified for safety operations. The beam system (torso) must also be safely stopped if the robot movements receive a safe stop command. Any unexpected start-up of the robot arms and the torso shall be prevented when being in “safe stop” status.

Laser scanners are installed near the base of the MRP in order to be able to detect the presence of people around the machine. If somebody is detected inside the area monitored by the laser scanners, all movements stop immediately. After getting away from the machine, the system waits two seconds and enables the restart of the functions of the machine (robot arms, torso or MRP). During operation of the robot arms and torso, the dimension of the protective fields around the machine is defined according to the range and the stop time of the robots and the torso.

From every side of the MRP an E-Stop has to be accessible. The E-Stop buttons shall stop the movements of the MRP as well as the movements of the robot arms and torso. After a pressed E-Stop button is released again, it will be necessary to press the Reset button in order to enable the machine to restart.

At normal operation, the robot and the torso are only enabled to operate if the MRP is a safe stop condition (with brakes on). The only exception is when the MRP is docked to the MPP station. In this case, the MRP will move straight together with the MPP while the robot arms execute operations on the MPP. In this specific case the protective fields around the vehicle are designed so that the area around the machine is protected, considering the movements of the MRP the robot arms and torso. The docking position of the MRP to the MPP station is safely detected with the use of safe detection fields of the laser scanners.

Risk Identified **-** *Being run over due to movement of the vehicle.*
Any presence surrounding the vehicle shall be detected, while MRP movements are enabled. In case of intrusion all movements should be stopped. During the movements of the MRP, the protective fields around the vehicle are defined according to the stop time of the MRP. When a person has moved out of the safety field, the MRP movement may be restarted automatically after a minimum delay of two seconds.

At normal operation, the MRP movements are enabled only if the robot arms and the torso are in safe stop condition and in the retracted safe position. The only exception is when the MRP is docked to the MPP station, as explained above. The retracted safe position of the robot arms and the torso are identified with safe position sensors. Any unexpected start-up of the MRP shall be prevented when being in “safe stop” status.

The size/extent of the safety fields need to be adapted according to the MRP speed and moving direction. Therefore, it is necessary to measure the speed and the orientation/angle of all four wheels.

As mentioned above, the E-Stop buttons have the same effect on the MRP as they have on the robot arms and torso. If any button is pressed, the MRP goes to safe stop condition. It is also necessary to press the Reset button after releasing the E-Stop buttons in order to enable the restart of the MRP.

A warning blinking light indicates when the MRP is moving. Two warning blinking lights indicate when the MRP is moving straight to the right or straight to the left.

3.2. Protective Measures on the MRP

The following Figure 3 shows an overview of the protective measures on the MRP in order to fulfil the safety requirements for the THOMAS pilot cases.

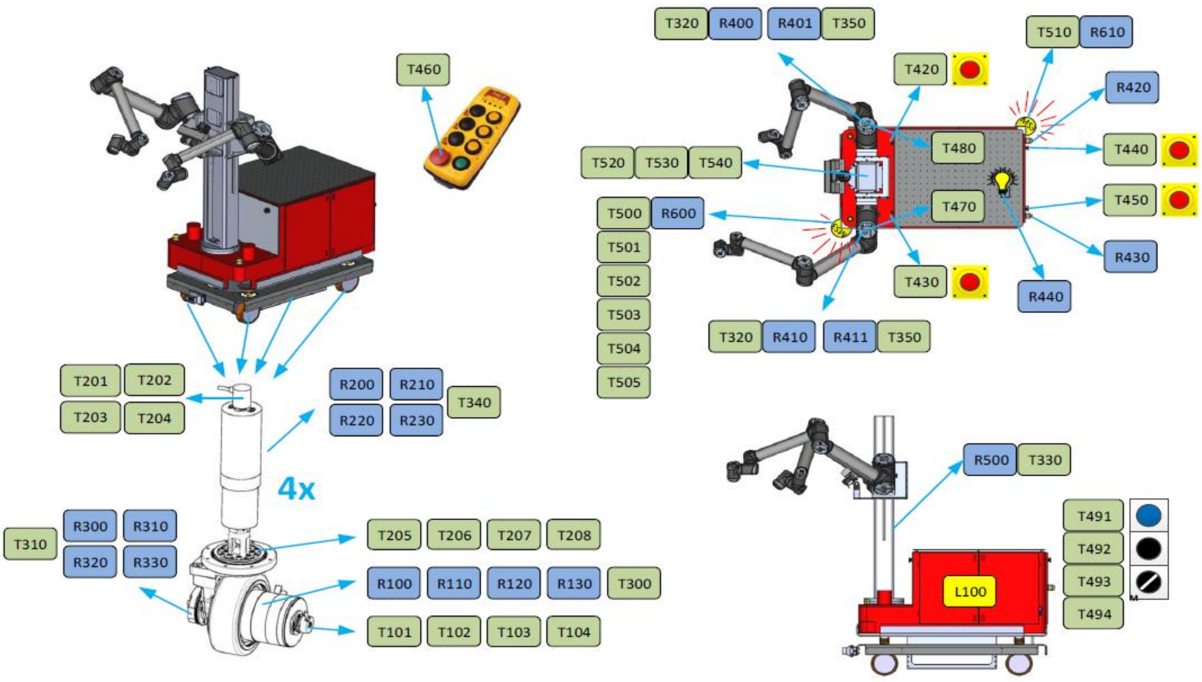

Figure 3: MRP protective measures

3.2.1. Triggers

Triggers (Txxx, green) are the safe outputs of safety-rated sensors. In order to safeguard the omnidirectional movement of the MRP, two safety encoders per wheel are required to safely measure the wheel orientation, wheel turning direction and wheel speed (T101-T208).

The MRP supports several operating modes (T493) and can be started and reset via corresponding push buttons (T491, T492). In order to stop the MRP manually in case of risk or emergency, several E-stop buttons are placed on all sides of the MRP as well as on the remote (T420-T460). The safe retracted positions of the two robot arms (T470-T480) and the torso (T520-T540).

Two SICK microscan3 safety laser scanners are deployed on diagonal ends of the MRP. They have several safety fields configured which are monitored for infringements (T500-T510).

3.2.2. Reactions

In order to slow down or stop the MRP in case of risk or emergency, respectively, each wheel has a relay for the motor drive, the wheel swerve motor and the wheel motor brake (R100-R330).

The motion of the robot arms (R400-R410) as well as of the torso system (R500) can be slowed down or halted in case of risk or emergency.

The safety laser scanners have different field sets that depend on the actual velocity and movement direction and get switched accordingly (R600-R610).

Visual signals indicate the direction of motion or when the MRP is moving at higher velocities (R420-R440).

3.3. Protective Fields

The design of the protective fields of the MRP are related to two main functions of the equipment: movement of the MRP and movement of the robot/torso set.

For basic operations, either the MRP or the robot/torso may move. To be able to move the MRP, the robot/torso set must be in the retracted position. To be able to move the robot/torso the MRP must be docked at one of the three workstations and the MRP not moving. Exception: the MRP is docked to the MPP station. In this specific case, the movement of the MRP and the robot/torso is allowed and the protective fields are adjusted accordingly.

3.3.1. MRP movement

It was defined a clearance between the MRP and the fixed objects on the work area of 500 mm or more around the MRP. This area is monitored by the laser scanners when the MRP is moving. This area is considered from the dimensions of the movement envelope of the MRP when the robots/torso are in the safe retracted position.

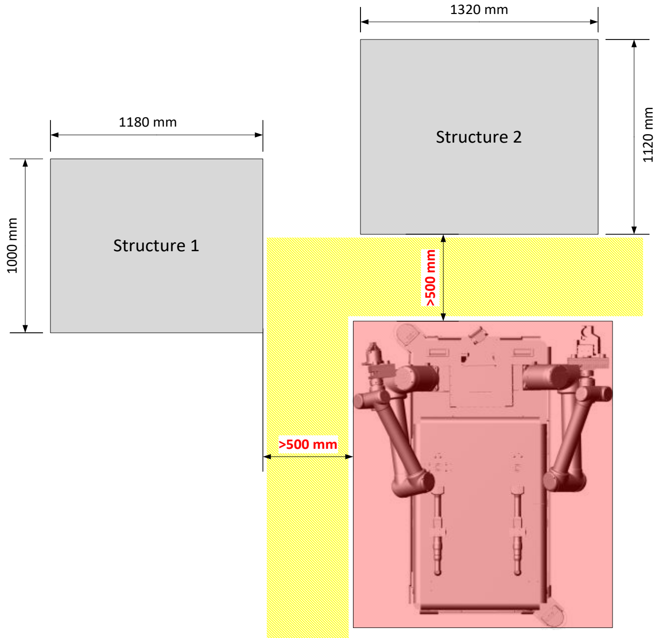

Figure 4: Safety area around the MRP

The simultaneous movement of the MRP and the robot/torso is allowed when the MRP is docked at the MPP station. In this case, the clearance between the MRP and the MPP is also more than 500 mm.

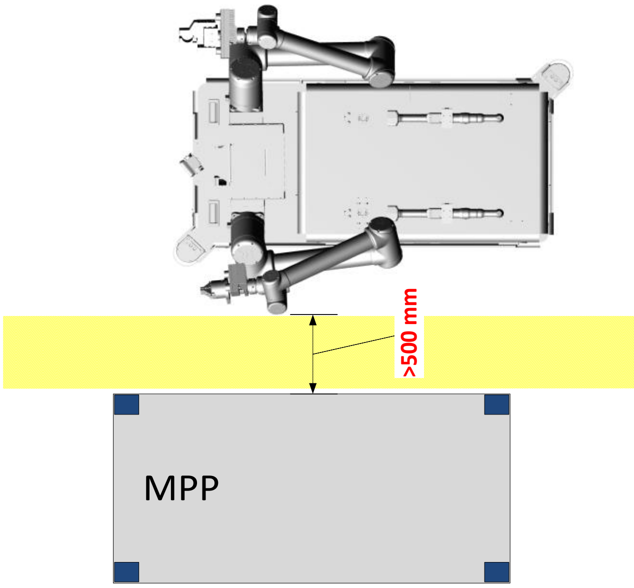

Figure 5: Safety area between MRP and MPP

The movement of the MRP (travel direction) defines the area around the MRP monitored by the protective fields. The encoders on the wheels detect the moving direction of each wheel and according to that, the protective fields around the operation envelope of the MRP are defined:

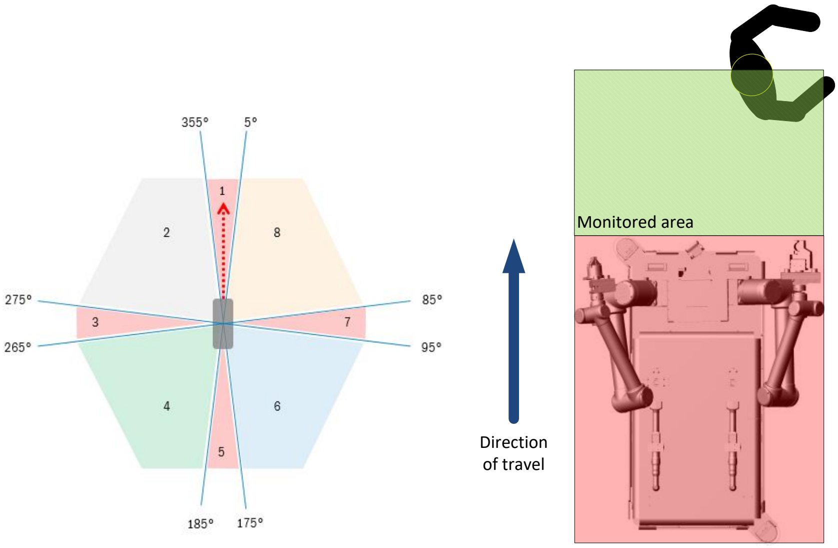

Figure 6: Protective fields around the MRP

Examples of the protective fields (red area) according to MRP moving direction:

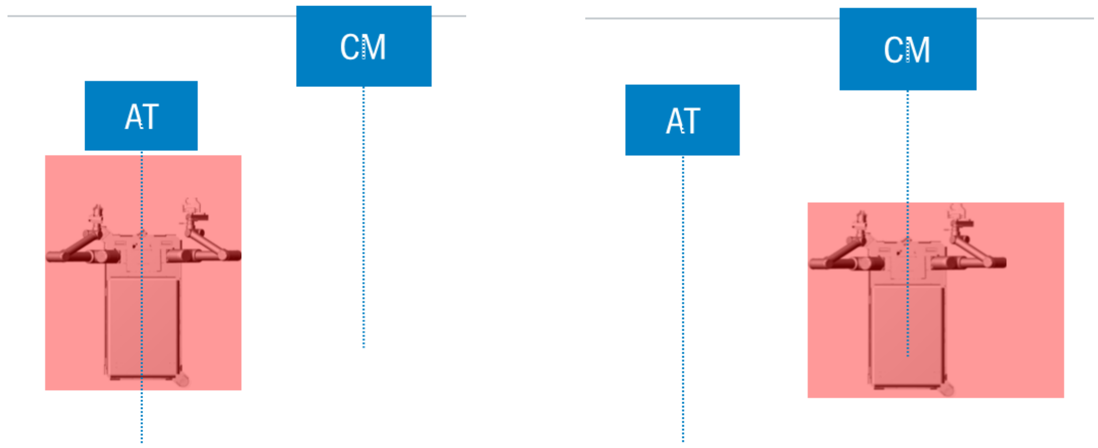

Figure 7: Protective fields (red area) according to MRP moving direction, Left: moving straight forward, right: moving to the right

In the cases of complex movements of the MRP, when the wheels are not ALL in one direction straight to the front, rear, left or right, the protective fields are designed to monitor the complete area around the MRP envelope, always considering the monitoring area of more than 500 mm around the envelope.

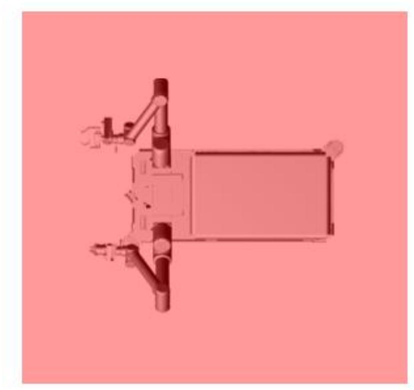

Figure 8: Protective fields when MRP's wheels are not in the same direction

The dangerous area around the moving MRP is divided in two parts, each one of them monitored by one laser scanner (front left and rear right).

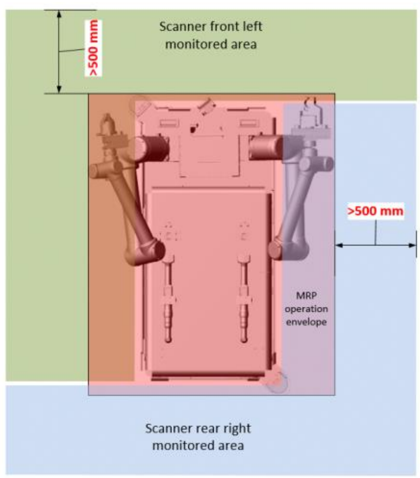

Figure 9: Dangerous areas around the moving MRP

3.3.2. Robots and torso movements

Besides the calculation of the minimum safety distance according to the stopping performance of the system, it was considered the movement envelope of the robot/torso movement. The length of the protective fields considers this envelope.

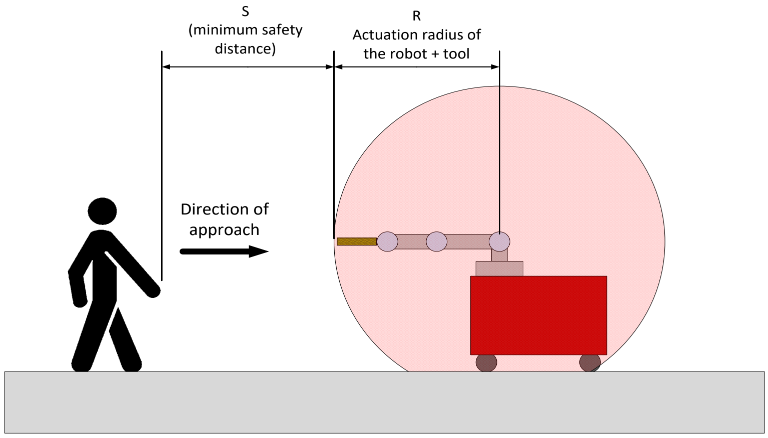

Figure 10: Protective field's dimensions

Minimum distance considering the movement envelope of one robot arm (left) and both robot arms (right):

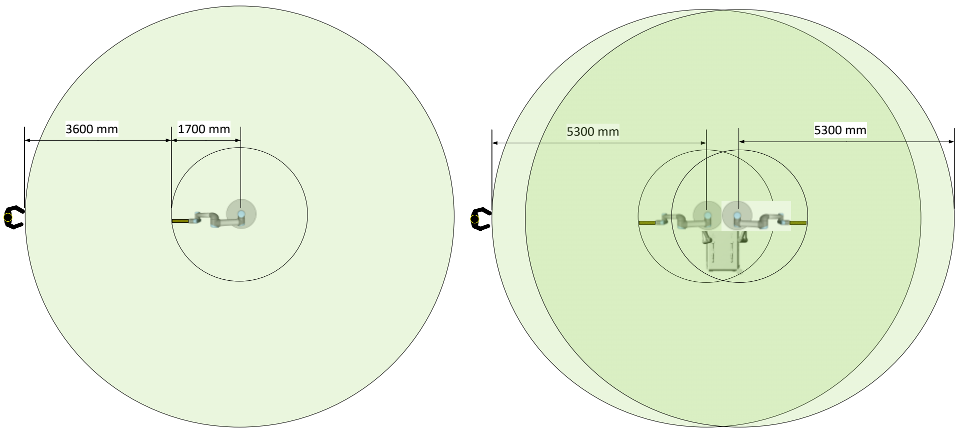

Figure 11: Protective fields based on robot's envelope

Minimum distance considering the movement envelope of both robots in the safe retracted position:

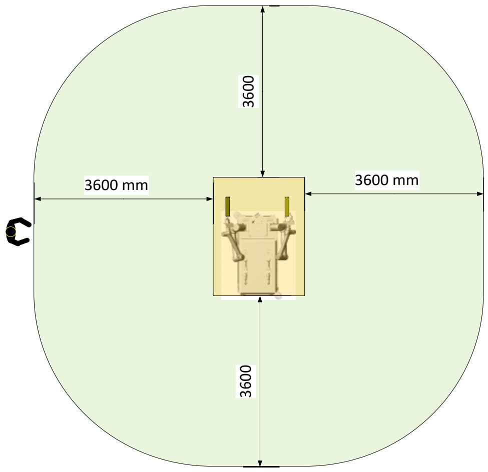

Figure 12: Minimum distance considering the movement envelope of both robots in the safe retracted position

During the movement of the robot/torso the protective fields don't change but are defined according to the environment of the workstation where the MRP is docked.

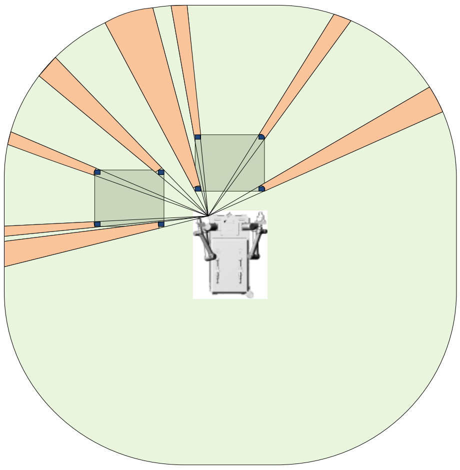

Figure 13: Docked MRP’s protective fields

Because of the "shadows" created by the different objects of the work area on the monitoring plane of the laser scanners it's important to provide additional protective measures to protect from the movement of the robot/torso people that could be undetected on these shadow areas.

3.3.3. Workstations detection

At each one of the three work stations – Assembly Table (AT), Compression Machine (CM), Mobile Product Platform (MPP) – a set of detection fields is designed to safely detect if the MRP are positioned in front of the table, so that the protective fields for operation of the robot/torso may be allowed. The "legs" of the tables are used to detect each station. An extra detection field is used between the legs of the tables and the MRP to be sure that no one is in this area.

3.3.4. Protective field set for each of the workstations

In Figure 14 the protective fields during MRP’s existence in each workstation of the layout are presented.

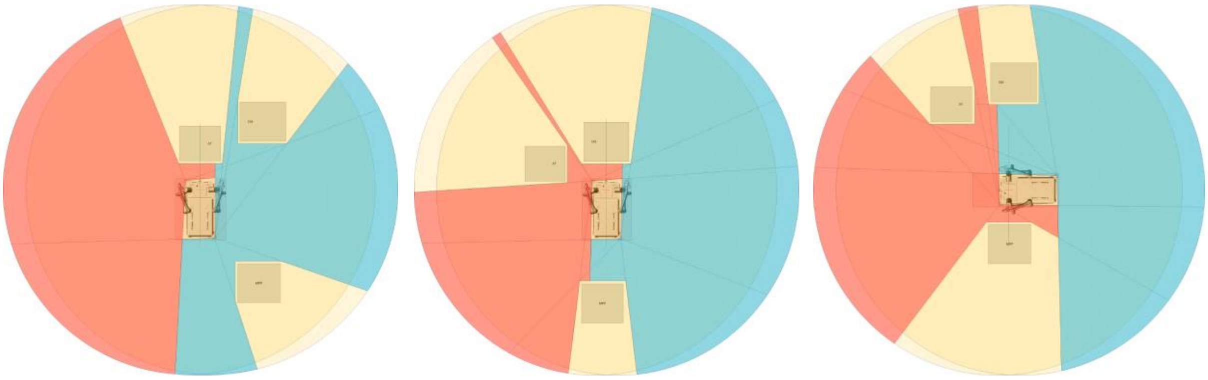

Figure 14: Protective fields for each workstation (Left: assembly table, Middle: compression machine, Right: mobile product platform)

3.4. Safety related application software requirements

This section describes the requirements for the functions and processes/flows of the safety related application software.

3.4.1. MRP movement

The movement of the MRP is detected by the safety encoders installed on the wheels. Depending on the speed and moving direction of each wheel, the protective fields are adjusted accordingly.

The swerve measurement of the wheels is divided in 8 sectors (Figure 15). Each wheel is individually monitored (swerve, speed and direction).

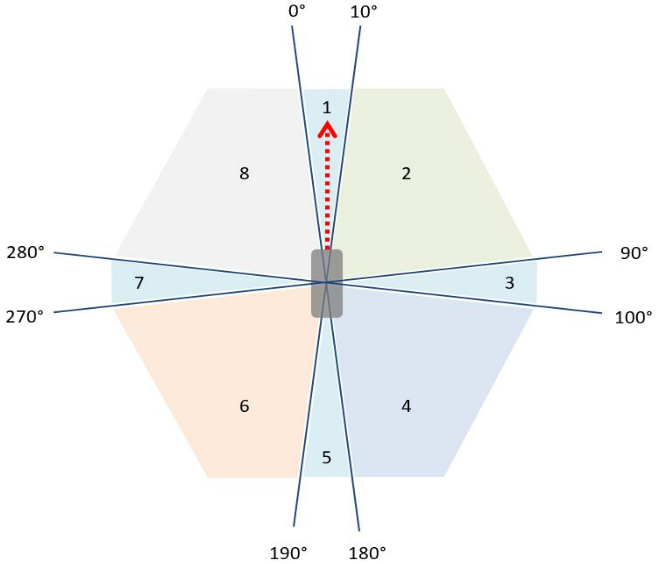

Figure 15:Wheels' swerve measurement

The results of the evaluation of the wheels measurements give the maximum speed of the fastest wheel and the moving direction of all four wheels.

According to the moving direction of the wheels, the scanners monitoring sectors must be activated:

For straight approach and departure movements of the MRP, the protective fields must be in the direction of travel, respecting the stop distance requirement and clearance to other structures.

For complex approach and departure movements of the MRP (curves or other wheel orientation combinations, the protective fields must be complete around the MRP, respecting the stop distance requirement and clearance to other structures.

Result:

- All four wheels moving to sector 1 (forward movement): Scanner 1 - Sector A activated
- All four wheels moving to sector 3 (movement to the right): Scanner 2 - Sector B activated
- All four wheels moving to sector 7 (movement to the left): Scanner 1 - Sector B activated
- All four wheels moving to sector 5 (backward movement): Scanner 2 - Sector A activated
- All other possible combinations of wheel orientation: All sectors activated, both scanners

According to the resulting speed of the MRP (fastest wheel) the length of the protective fields are defined:

- Standstill = All monitoring sectors of both scanners activated, with short length.
- Wheel moving = long protective field, according to the moving direction of the wheels (explanation above).

If the maximum allowed speed is reached, an e-stop of the complete system is activated. After that, the reset button must be pressed in order to enable the start function again.

If a person (not moving toward the vehicle) is detected inside the monitored area in the direction of travel of the MRP, the vehicle must completely stop before contact with the stationary person. If the MRP stopped because of the presence of a person/object, after the protective fields are free again, the vehicle may start automatically after 2 seconds.

The MRP is only able to move between the workstations (not docked to any station) if the respective protective fields are not infringed and if the robot and torso systems are in the retracted safe position. If at any moment the robots or torso are out of the retracted safe position and the MRP moves it will complete stop the system (E-Stop). Only after positioning the robots and torso at the safe retracted position again (in manual mode) and pressing reset the MRP will be able to be restarted.

3.4.2. Robot and torso movement

The laser scanners monitor continuously the area around the MRP. The detection fields are responsible to detect the docking of the MRP to the workstations. According to the combination of infringed detection fields, the safety control system will determine in which station the MRP is docked and activate the respective protective fields set.

3.4.3. Operating modes – Automatic, Manual, Setup

The description of the software requirements above are related to the automatic operating mode. During manual mode, all functions of the MRP are released without the protective field monitoring. In setup mode only the brake system of the wheels is released, so that the MRP can be pushed manually without power.

When changing the operating modes or in case that and E-stop button is pressed, then the complete system must stop, and the reset button must be pressed so that the start function may be enabled again.

3.4.4. Visual signalling

If one of the four wheels is moving, in any direction, a visual signal indicates this behaviour.

If all four wheels are moving to sector three (movement to the right), the right lamp will indicate this.

If all four wheels are moving to sector seven (movement to the left), the left lamp will indicate this.

3.5. Electrical design

THOMAS MRP electrical design is up to date including information about all components' connectivity with MRP's controller (Figure 16).

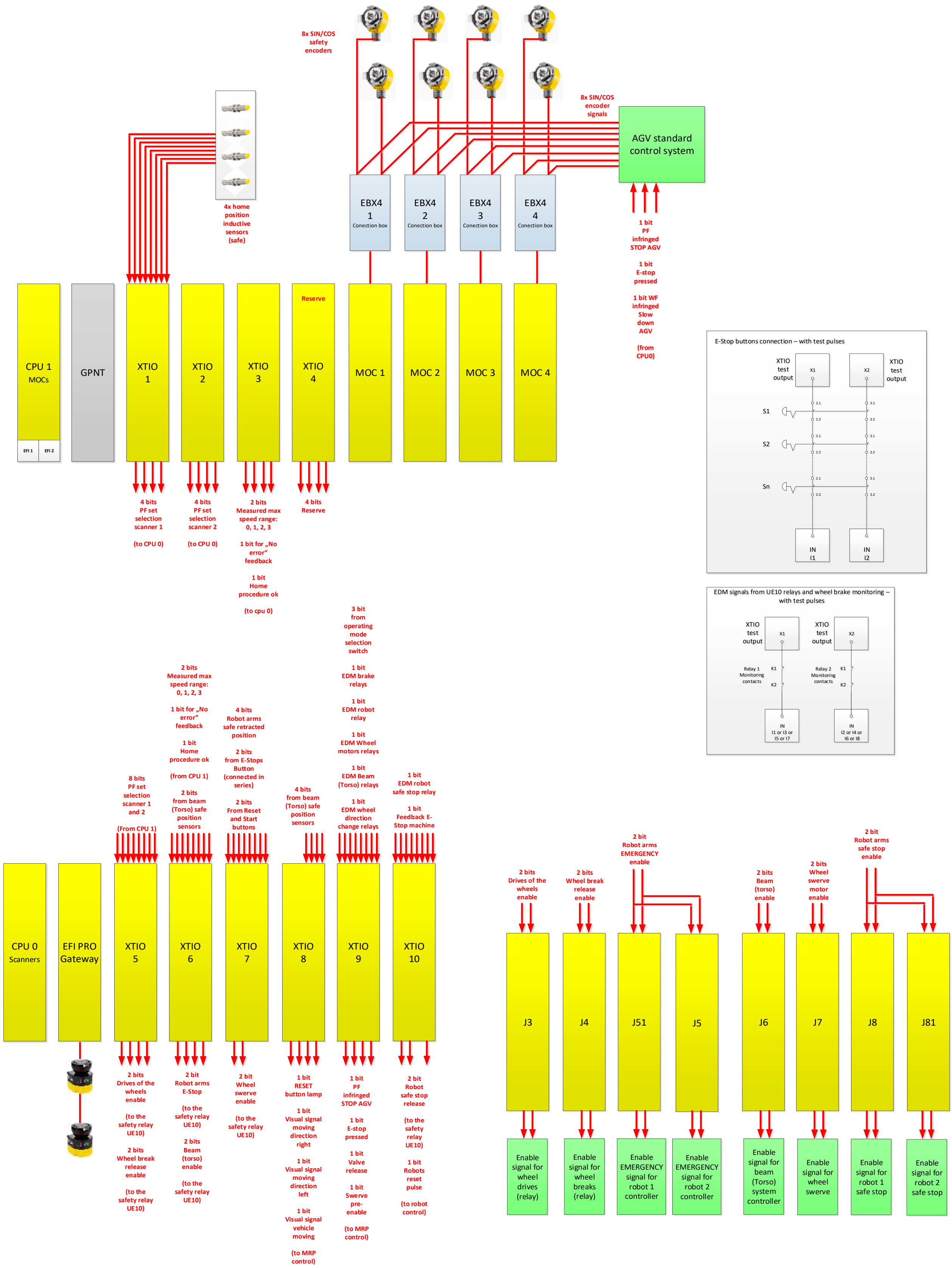

Figure 16: Electrical design

3.6. Relevant Standards

THOMAS safety system based on some safety standards. These standards are being presented in the following table.

Table 1: Relevant standards

Standard	Year	Title/Reference
EN ISO 12100	2010	Safety of machinery – General principles for design – Risk assessment and risk reduction
EN ISO 13849-1	2015	Safety of machinery – Safety-related parts of control systems – Part 1: General principles for design
EN ISO 13849-2	2012	Safety of machinery – Safety-related parts of control systems – Part 2: Validation
EN 62061	2005	Safety of machinery – Functional safety of safety-related electrical, electronic and programmable electronic control systems
EN 60204-1	2006	Safety of machinery – Electrical equipment of machines – Part 1: General requirements
EN ISO 13857	2008	Safety of machinery – Safety distances to prevent hazard zones being reached by upper and lower limbs
EN ISO 13855	2010	Safety of machinery – Positioning of safeguards with respect to the approach speeds of parts of the human body
EN ISO 13850	2015	Safety of machinery – Emergency stop function – Principles for design
IEC 61496-1	2012	Safety of machinery – Electro-sensitive protective equipment – Part 1: General requirements and tests
IEC 61496-3	2018	Safety of machinery – Electro-sensitive protective equipment – Part 3: Particular requirements for active opto-electronic protective devices responsive to diffuse reflection (AOPDDR)
EN 1525	1997	Driverless industrial trucks and their systems
ISO 10218-2	2011	Robots and robotic devices -- Safety requirements for industrial robots – Part 2: Robot systems and integration
ISO/DIS 3691-4	2018	Industrial trucks – Safety requirements and verification – Part 4: Driverless industrial trucks and their systems (DRAFT)

3.7. Installation

The following photos document the mounting and installation of the safety hardware on the MRP.

Figure 17: MRP electrical cabinet

Figure 18: Close-up of SICK safety PLCs in the MRP cabinet

Figure 19: safety encoder for wheel orientation

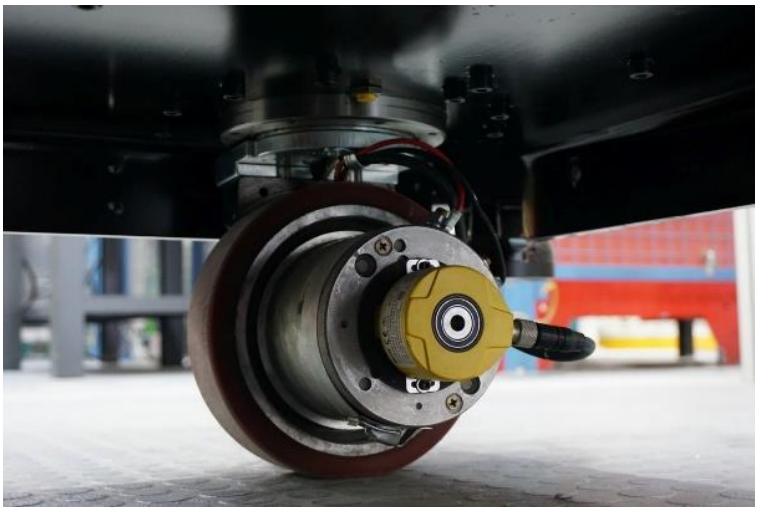

Figure 20: safety encoder for wheel speed

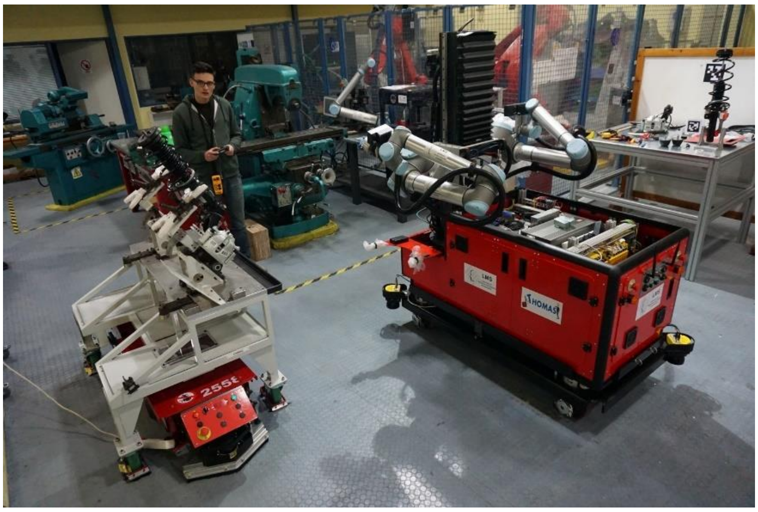

Figure 21: MRP with two SICK microscan3 safety laser scanners on opposite ends

4. End-Effector Safeguarding

SICK has been developing a new safety solution for end-effector safeguarding that addresses the safety at the end of the robot arm. This safety solution can be used in scenarios, which are not covered by the MRP safeguarding means mentioned above. In particular, end-effector safeguarding (EES) can for instance be used to mitigate the risk of crushing the operators' hand between the robot tool and the working surface.

4.1. Motivation

Power and force limitation reduce the extent of damage occurring due to unwanted contact of the operator and the Cobot to an acceptable level. Generally, this does not include the end-effector. The choice of the tool depends on the individual application. Design and construction might not be inherently safe. Thus, the risks related to the applied tool or work piece are not necessarily covered by the Cobot's safety functions. Possible risks – like squeezing the operator's hand – must be reduced to an acceptable level.

SICK's approach to solve such applications is the EES. The EES provides an intelligent speed control and the possibility of automatic restart of the application. This reduces unwanted standstill and ensures short process times. Furthermore, the EES provides a high level of flexibility. It offers an appropriate safety solution for a large number of different tools and applications. Hence, no investment in cost intensive and specially designed human-robot-collaboration tools is necessary.

4.2. Installation

In total, the EES system consists of the sensor, an accompanying adapter flange and counter ring to mount the sensor on the standard robot flange. One particular challenge was the integration on the robot arm with the Roboception stereo camera in place. A redesign of the camera mounting solved this issue so that the middle part does not infringe the neighbouring scan fields.

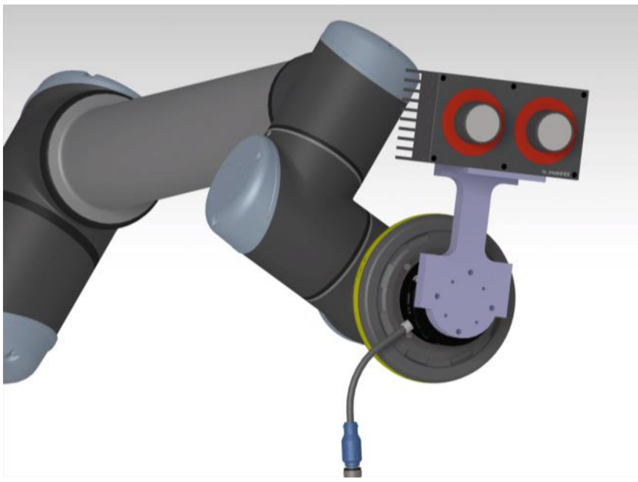

Figure 22: End-effector safeguarding prototype, newly designed ROBOCEPTION rc_visard camera mounting that does not infringe the EES field

5. 3D SAFETY

5.1. Motivation

The current safety solution for the compression machine in the PSA pilot case consists of a fenced area (three sides), safety light curtains (one side), and a confirmation button to be pushed when the worker has completed his tasks and that the compression area is free of other workers, as sketched in Figure 23.

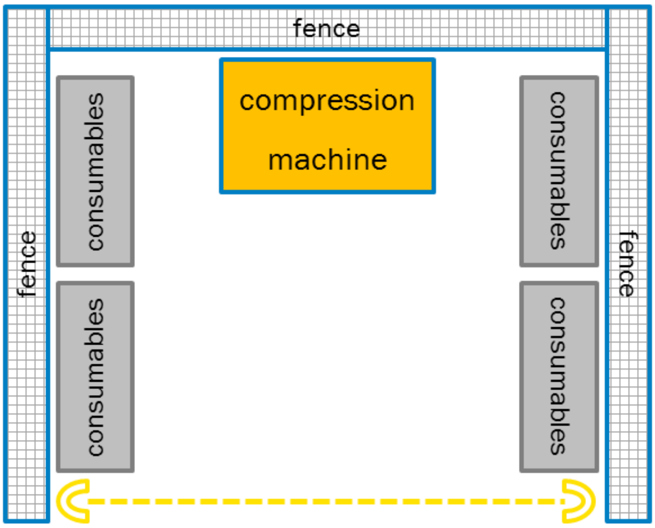

Figure 23: Schematic of the current workspace at the PSA compression machine

SICK has been investigating the potential application of a 3D safety camera, which is currently under development, so that the workspace at the compression machine could be radically redesigned into an unfenced, open workspace (Figure 24 and Figure 25). Objects intruding the safety related field of view will be detected, enabling the safety control to take safety-related, situation-dependent decisions such as slowing down or stopping the hazardous machine.

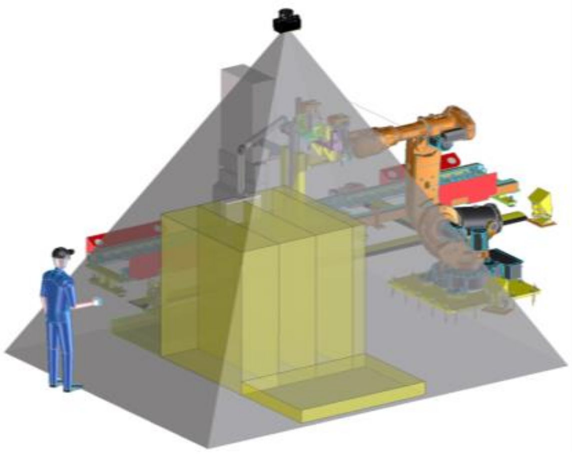

Figure 24: SICK 3D safety camera and monitored work area (schematic)

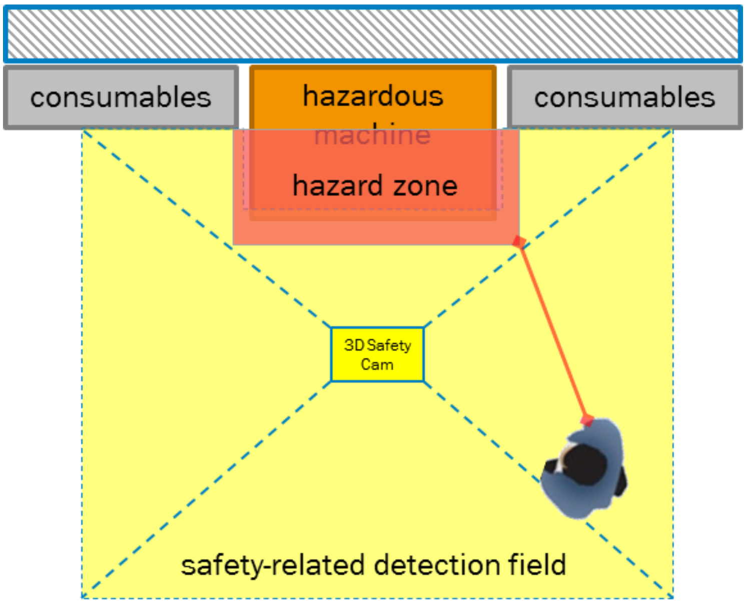

Figure 25: Schematic of the envisioned open workspace at the PSA compression machine

The 3D safety camera detects objects down to the size of an arm and outputs the minimum distance to a predefined contour of a hazardous machine (e.g. the compression machine). Based on suitable thresholds of this minimum distance, the hazardous machine can be slowed down or halted completely.

5.2. Object detection and marker based MRP detection

To enable sophisticated situation-dependent behaviour an object classification is performed by the 3D safety camera. This allows taking different safety-measures for *human* and *non-human* objects. This means that the hazardous machine is halted if a worker is approaching. On the other hand if the MRP approaches the machine (e.g. to unload the work piece after processing) the production process can be continued as no safety risk for human beings exists. Thus, the ability to distinguish between workers and the MRP allows for an uninterrupted production process while not compromising the workers safety in any way.

The classification of approaching objects always defaults to *human.* Only if the MRP is detected the classification outputs *non-human*. The detection of the MRP is based on optical markers. As marker detection was not the primary goal during the development of the 3D safety camera, certain limitations had to be considered during the selection of a marker type. One limitation is that the infrared dot pattern used to obtain depth information about the captured scene also covers the markers that are to be detected. In addition, the resolution of the captured images is designed to detect arm-sized objects. To ensure a robust detection of the markers, concentric contrasting circles (see Figure 26) with an edge length of 100 mm are chosen over information carrying markers (e.g. Aruco Marker).

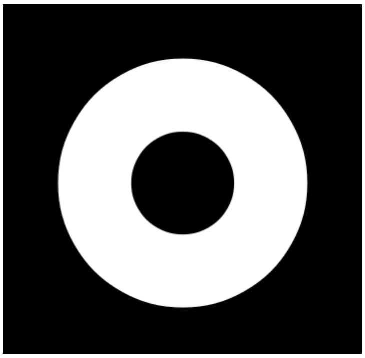

Figure 26: Contrasting concentric circle. A simple marker type that is detected robustly using the 3D camera

The marker detection is performed by searching circular black and white shapes in an image. Subsequently the centres of the shapes are analysed. A marker is detected if the centres of a black and a white shape match. Prior to the shape search, an image processing chain is applied.

The image processing for detecting the concentric circle markers within the captured images is implemented using algorithms provided by the open source library OpenCV. The processing chain includes several steps and aims to be robust against varying lighting conditions. Figure 27 illustrates the major stages of the image before the markers are searched. The top left image shows the input image as captured by the 3D safety camera.

Then the background is subtracted using the depth information and a low pass filter is applied. After equalizing the histogram (bottom left), a binary image is generated using an adaptive threshold. In the last stage a morphologic opening is performed (top right). The detected markers are highlighted in the bottom right picture.

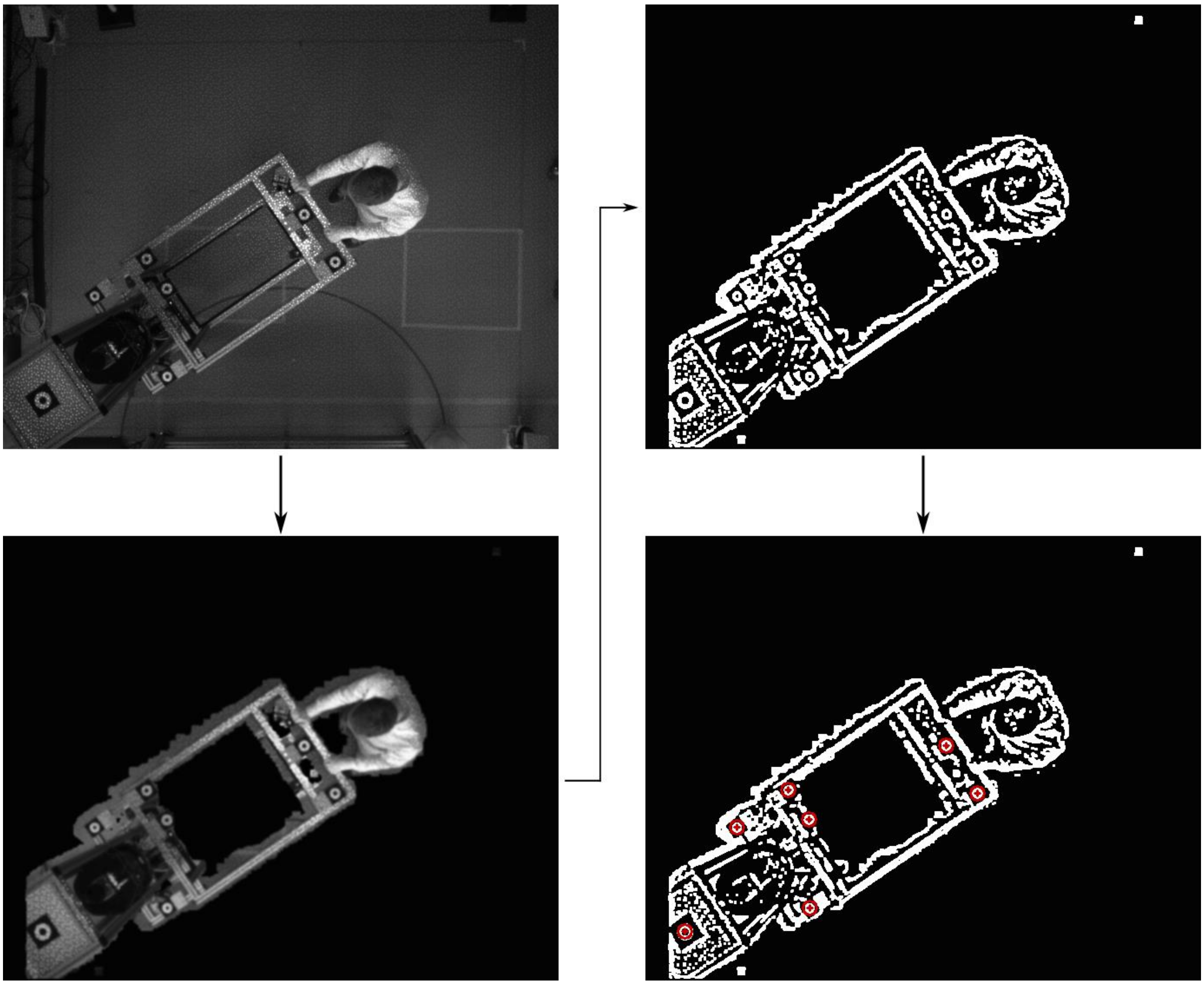

Figure 27: Major steps of the image processing chain to detect concentric contrasting circles. Top left: Input image captured by the 3D camera (a non-safe SICK Visionary-S with similar optics and measurement principle has been used for algorithm development). Bottom left: Background subtracted, low pass filtered, histogram equalized. Top right: Dynamic threshold and morphological opening applied. Bottom right: Marker detections by matching the centres of circular black and white shapes.

After detecting the single markers, the arrangement of the markers is analysed. Since the markers itself do not encode any information, the identification of the MRP is done by performing a rigid body fitting. The rigid body fitting evaluates if the detected marker arrangement is equivalent to the marker arrangement that is installed on the MRP. This is done by checking for every single marker individually if it is a part of the known arrangement.

The identification of every single marker is done by evaluating its pairwise distance from the other markers. To make this possible the arrangement of the markers has to follow certain design criteria. The arrangement has to be designed in a way that the set of pairwise distances between the markers is unique for every single marker. Figure 28 depicts a minimal example of a marker arrangement that fulfils these design criteria. All pairwise distances between the markers are unique. Every marker (m_1, m_2, m_3) can be identified by its distances to the other markers. If the measuring of the distances for a marker returns d_12 and d_23, the examined marker is m_2. Table 2 lists the set of distances that identify every marker in the minimal example of Figure 28.

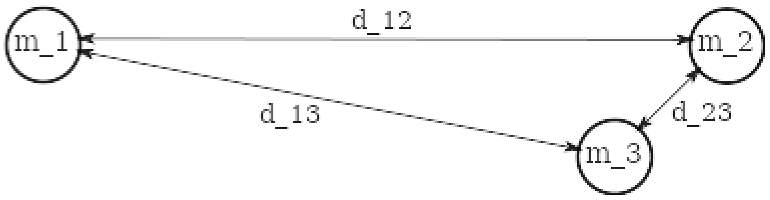

Figure 28: Example arrangement of markers. The set of pairwise distances between the markers is unique for every single marker. Thus, every marker can be identified by its distances to the other markers.

Table 2: Set of pairwise distances to identify markers in the multi marker arrangement depicted in Figure 28

Marker	Pairwise distances
m_1	d_12, d13
m_2	d_12, d_23
m_3	d_13, d_23

The more markers are part of a multi marker arrangement the more complex it gets to design the arrangement in a way that the pairwise distances are unique. As Figure 27 shows, the arrangement that is used to identify the MRP, consists of seven markers. Compared to the minimal example this increases the number of pairwise distances from three to twenty-one. To ensure the uniqueness of pairwise distances a tool is used to generate the marker design. By mounting the markers on three different height levels an additional feature is added that can be used to distinguish between the markers.

On the other hand, mounting markers on different heights leads to a perspective distortion of the marker arrangement. In order to still be able to measure of the distances between the markers a perspective correction is performed. By using the depth information, all markers are projected perpendicular to the floor. The projected marker positions are invariant to the position of the MRP within the field of view of the camera. Figure 29 depicts the effect of the perspective distortion. The centre image shows a plain top down view onto the marker arrangement that is free of any distortion. The blue circles in the left and the right image show the impact of the perspective distortion to the marker arrangement. The red circles show the projected marker positions and are equivalent in both images. Therefor the projected marker positions are used to measure the distances between the markers.

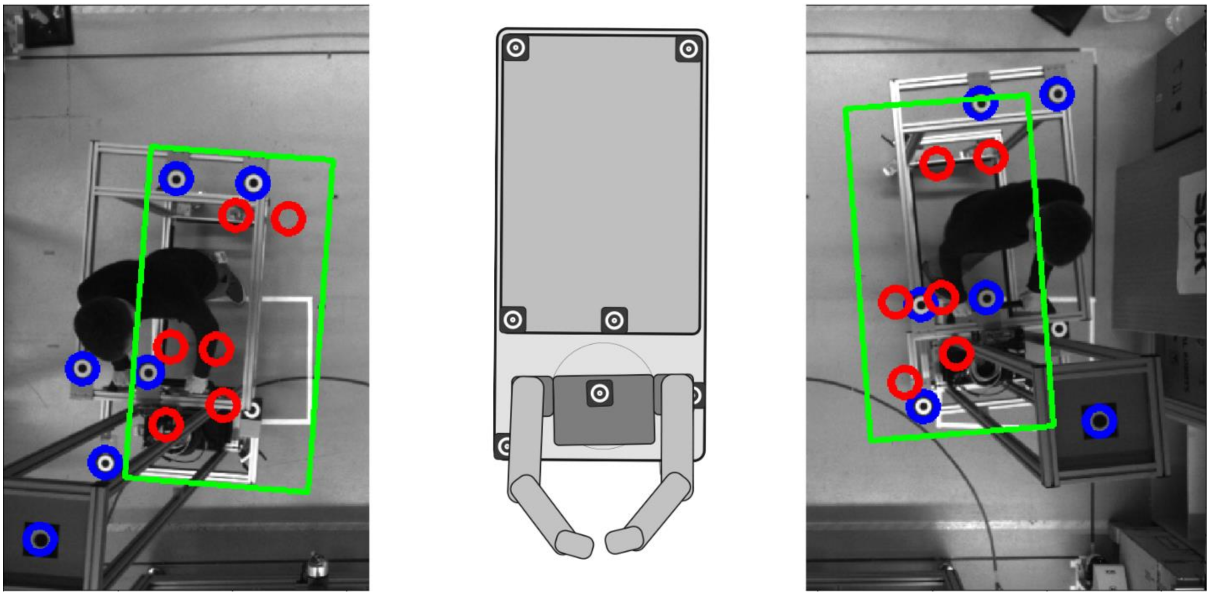

Figure 29: The centre image shows a plain top down view onto the marker arrangement. The left and the right image show the perspective distortion of the marker arrangement when the MRP is on the left and the right side within the field of view. The blue circles highlight the detected markers. The red circles show the perpendicular projection of the blue circles onto the floor. While the arrangement of the blue circles is different in the left and the right image, the arrangement of the red circles is the same.

In practice, single markers will often be occluded, for example if the MRP enters or leaves the field of view or the robotic arms obscures the view. The developed system proved to be robust against occlusion since it is not necessary to detect all markers at the same time. To determine the position and the rotation of the MRP only a subset of two of the seven markers needs to be identified. To identify two markers in a plane by their pairwise distances at least three markers need to be detected (see the minimal example in Figure 28). If two markers are mounted on different heights, no third marker is needed to clear the ambiguity.

By an artificial increase of the number of required markers, the difficulty to maliciously manipulate the MRP detection can be increased. The difficulty to fake a marker arrangement increases with the number of markers and large pairwise distances. Therefore, the number of required markers can be seen as a tuning parameter for the certainty of the MRP detection.

If the required number of markers is detected and the installed marker configuration can be fitted into the detected marker arrangement the position and rotation of the MRP is estimated. Since the shape of the MRP is known it is then possible to mute the worker detection within the area of the MRP. Figure 30 continues the image processing chain shown in Figure 27. The top image depicts the perpendicular projection of the detected markers on the floor. The bottom image highlights the detected MRP.

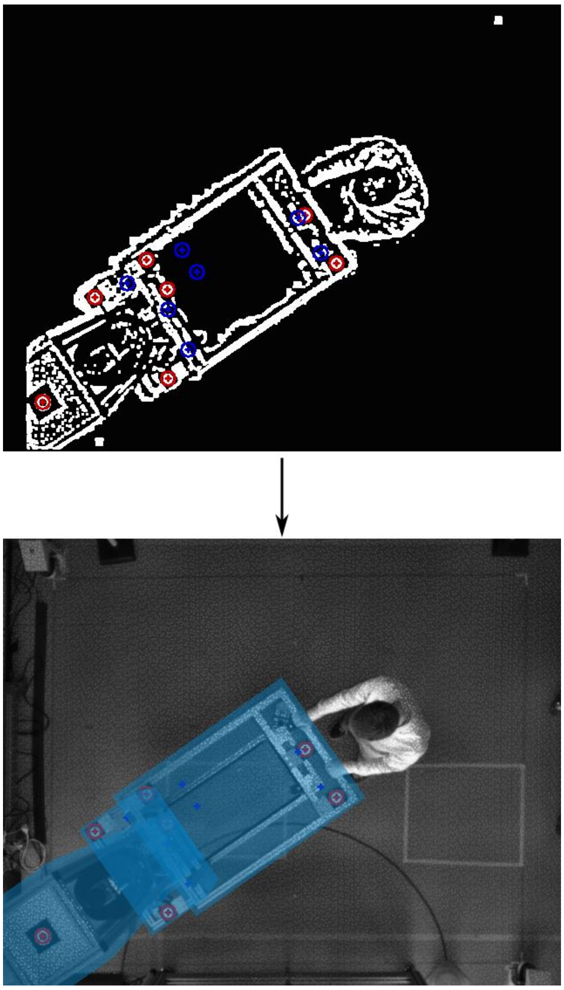

Figure 30: The top image shows the detected markers (red) and the perpendicular projected markers (blue) that are used to analyse the marker arrangement. The bottom image shows the MRP that was detected by fitting the installed marker arrangement into the detected marker arrangement.

6. SUMMARY AND OUTLOOK

The main purpose of this demonstrator deliverable is to describe the concepts and the safety systems for the THOMAS pilot cases.

A first Machine Safeguarding Evaluation (MSE) was carried out at PSA by SICK to identify potential risks and corresponding risk reduction measures. Based on this MSE, a product-neutral draft safety concept has been elaborated for the THOMAS MRP as the main entity of the two pilot cases. Subsequently, the safety concept has been translated to a product-specific safety design that was implemented in the MRP at LMS.

Apart from safeguarding the motion of the MRP, the robot arms on the MRP with its tools such as grippers need additional consideration with regard to safety. SICK has developed an end-of-arm safeguarding system that particularly safeguards the end of the robot arm with its tool. If definable safety distance thresholds to the robot tool are reached, the robot arm can be triggered to slow down or completely stop in order to avoid a collision with the worker.

Finally, SICK aims at the deployment of a prototypical 3D safety camera at the damper compression machine in the THOMAS PSA pilot case as an example on how to efficiently safeguard collaborative workspaces in an open, unfenced manner. In order to further increase efficiency, a marked-based detection of the MRP has been developed based on the camera’s 3D depth data so that the safety functionality can be muted if only the expected MRP infringes the monitored safety volume.

In conclusion, several complementary safety systems have been and continue to be developed at SICK to ensure the safety of the production processes considered in the two THOMAS pilot cases. Special attention is given to safeguarding the MRP and its robot arms as the central entity of the THOMAS concept. First versions of the risk assessment, the safety concept and safety design have been elaborated and are being integrated into the MRP.

In the final year of the project, the demonstrator setup will move to PSA as the end user. This requires that the MRP on-board safety is adapted to the operation environment at PSA. Furthermore, the end-of-arm safeguarding system will be integrated into one of the two robot arms and will be adapted to the tasks demonstrated in the automotive pilot case. Third, the 3D camera installation will be transferred to PSA or it will possibly be directly replaced by a 3D safety camera prototype and will be adapted to the specific operation environment at PSA.

7. GLOSSARY

3D	3-Dimensional
AT	Assembly Table (PSA pilot case)
CM	Compression Machine (PSA pilot case)
EES	End-effector Safeguarding
MPP	Mobile Product Platform
MRP	Mobile Robot Platform
MSE	Machine Safeguarding Evaluation
PLC	Programmable Logic Controller
PSA	Peugeot Société Anonyme

8. REFERENCES

[1] SICK THOMAS Deliverable D2.4, 2018.