Open-Digital-Industrial and Networking pilot lines using modular components for scalable production

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Summary:

This document presents the design and initial prototypes of ODIN core enabling technologies for perception enabled reconfigurable resources. The autonomous and mobile manipulators, reconfigurable tooling and modules for achieving environment and process perception which will be used in ODIN are presented in detail.

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EXECUTIVE SUMMARY

The main purpose of this document is to provide an overview of the initial prototypes of the ODIN core enabling technologies for perception enabled reconfigurable resources. In more detail, the following technologies will be presented in this document:

- Autonomous mobile manipulators (selection/design and customization) [Task 2.1]
- Reconfigurable robot tooling [Task 2.2]
- Robotic perception for the environment, process and human [Task 2.3]

This document describes basic aspects of the technologies in use based the requirements coming from the use case analysis as presented in D1.1 and describes the high-level pipelines used for solving the challenges. The initial prototypes' implementation in a preliminary version of ODIN small scale pilots' setup at technological partners premises will be presented.

Finally, the next steps to integrate the designed solutions into the overall ODIN software system are presented.

LEGAL DISCLAIMER

1. INTRODUCTION

Three different pilots are considered in ODIN namely a) Automotive pilot (STELLANTIS), Aeronautics pilot (AEROTECNIC), and c) White Goods pilot (WHEMEA). All ODIN pilots require advances and developments of autonomous and mobile manipulators, reconfigurable tooling and modules for achieving environment and process perception.

This deliverable presents the results of the design and prototypical implementation of such components but also describes their initial prototype application in the different ODIN pilots up to M18 of the project.

The developments which are presented in this document are organized in three groups:

- Autonomous mobile and robotic manipulators. Section 2 presents an overview of the current progress in the selection, design and customization of the manipulators that will be used in the ODIN pilots, with particular reference to their navigation skills.
- Reconfigurable robot tooling. Section 3 provides an overview of the current status of the ODIN reconfigurable robot tooling module and the design principles for ODIN tools design and selection.
- Robotics perception of the environment, process and human. Section 4 describes the design and prototypical implementations of the perception skills required in the ODIN pilot lines, including e.g. object detection and pose estimation based on CAD models, object inspection of Aeronautics mechanical assemblies, and human motion detection.

The implementation and deployment of the hardware and software core enabling technologies is also presented for each ODIN pilot line:

- Automotive pilot in Section 5,
- Aeronautics pilot in Section 6,
- White Goods pilot in Section 7.

2. AUTONOMOUS MOBILE AND ROBOTIC MANIPULATORS

2.1. Overview

This section provides an overview of the current developments in the selection, design and customization of autonomous mobile manipulators but also robotic manipulators that will be used in the ODIN pilots. The required platforms' integration per each ODIN pilot is presented in sections 5, 6, and 7.

The autonomous mobile and robotic manipulators that will be deployed to the ODIN pilots are the following:

- COMAU mobile manipulator
- AIC mobile manipulator
- TECNALIA mobile manipulator

They will be individually described in the following sections, with particular reference to new developments with respect to previous deliverable D1.3 "ODIN hardware architecture design".

Additionally, a short overview of safety functions for integration of mobile manipulators is presented in the respective pilot sections 5, 6, and 7. These safety functions are also detailly described in deliverable D5.1 "Report on the Risk Assessment performed in the design phase of the ODIN Pilot Lines".

2.2. COMAU mobile manipulator

The novel mobile platform prototyped by COMAU is the result of two robotic resources' integration made by COMAU itself namely the Agile 1500 AGV and the Racer5 Cobot.

COMAU Racer5 Cobot (Figure 1, left) is a small robotic arm with a payload of 5 kilos. It provides a reach of 0.8 m and an accuracy of 0.03 mm. COMAU Racer5 Cobot is able to switch from collaborative to non-collaborative speed during operation through the usage of a safe signal.

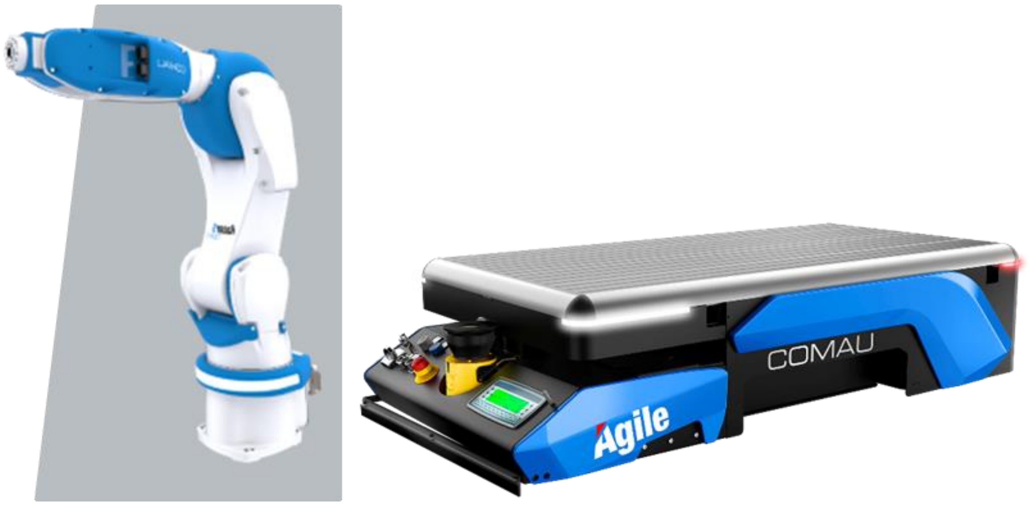


Figure 1: COMAU Racer5 Cobot (left) and Agile 1500 (right)

The COMAU Agile 1500 (Figure 1, right) is an AGV able to move freely in a closed space using natural navigation technology based on laser scanner sensors. The vehicle's differential drive architecture allows good stability and manoeuvrability. It is capable of transporting up to 1500 kilos of payload and can withstand a maximum towing force of 2100 N.

More information about the single robotic resources, together with the specifications and dimensions, can be retrieved in Section 2.1.1 of D1.3 "ODIN hardware architecture design". The following section will focus on current status, developments and next actions.

Development status

During the last months, COMAU efforts were focused on the designing of the mechanical components and electrical wirings, as well as the software integration between the two robotic resources.

Figure 2: COMAU Mobile Platform prototype

In more details, the work carried out until M18 of the project can be briefly summarized as follows:

- Implementation of a secondary battery for the robot and design of a custom double-charger.
- Connection of an additional inverter to power the Cobot's AC motors.
- Connection and programming of an additional Safe PLC to manage the additional safety components as well as the switching of the collaborative to non-collaborative mode of the Cobot.
- Routing of all the hardware components to the AGV's Canbus line.
- Implementation of the connection between the Cobot and the AGV through Canbus I/Os.
- Implementation of a collaborative gripper and programming of a demo routine (Figure 3).

Figure 3: COMAU Mobile Platform demo setup

The next actions that will allow the consolidation of this technology involve further testing, improved outer chassis with fixtures for trays and additional tooling, as well as the development of a dedicated software module for the external control of the platform.

Software interfaces and developments

As mentioned in Section 2.1.1 of D1.3, the communication with Racer5 Cobot is based on TCP/IP through a socket and PDL2 commands. This is exploited by the COMAU-ROS driver, a package that monitors both the robot status in terms of pose and the task status, in order to maintain an updated knowledge of the system state. Moreover, it waits for new motion commands coming from the Motion Handler and passes them to the robot.

The connection of the mobile platform will not be established through a physical Ethernet port, but using the Wifi module of the AGV. The data will be routed to the correct IP address and this will allow the use of the wireless infrastructure already available in the platform.

A similar approach to the Cobot will be exploited for the control of the Agile 1500. A ROS sub-module is under development and will be integrated in the COMAU-ROS driver. In this case, the messages will not be PDL2 commands, but 8-byte messages that the PLC on board of the Agile will decode and process. This approach is due to the hardware architecture of the Agile, which uses a Kollmorgen CVC600 vehicle controller / PLC to manage the behaviour of the platform.

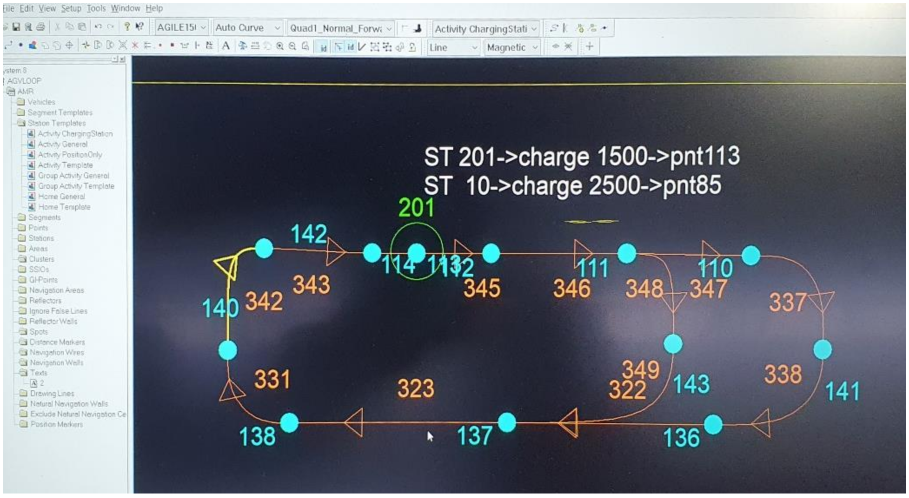


Figure 4: Kollmorgen's Layout Designer

The vehicle controller is programmed offline and stores the map of the surroundings, the nodes and paths that the vehicle will use to navigate (Figure 4), all of which is programmed with the proprietary software Layout Designer by Kollmorgen. This data can be used by the ROS driver in order to send “Go to Goal” commands with target being the desired node number. An extract from the preliminary list of messages that the AGV will send and receive is shown in Figure 5.

Safety components of the mobile platform

As documented above, the safety of the mobile platform is ensured by the safe PLC installed on board of the Agile 1500, as well as the additional safe PLC that controls the collaborative to non-collaborative switching of the Cobot. The block diagram of the safety system is presented in Figure 6.

Parameter	Parameter Path	Datatype
BatterySoC	NDC8.UserDefined.BatterySoC	DINT
DestPoint	NDC8.Automatic.DestPoint	DINT
Point	NDC8.LayoutPosition.Point	DINT
Segment	NDC8.LayoutPosition.Segment	DINT
X	NDC8.Position.X	DINT
Y	NDC8.Position.Y	DINT
Angle	NDC8.Position.Angle	DINT
MotorSpeed	NDC8.ACS_5.MotorSpeed	INT
DriveEncSpeed	NDC8.ACS_5.DriveEncSpeed	INT
Moving	NDC8.VehicleControl.Moving	BOOL
CurvatureLimit	NDC8.TurnSignal.CurvatureLimit	DINT
RightTurn	NDC8.TurnSignal.RightTurn	BOOL
RightTurnDistance	NDC8.TurnSignal.RightTurnDistance	DINT
RightTurnCurvature	NDC8.TurnSignal.RightTurnCurvature	DINT
LeftTurn	NDC8.TurnSignal.LeftTurn	BOOL
LeftTurnDistance	NDC8.TurnSignal.LeftTurnDistance	DINT
LeftTurnCurvature	NDC8.TurnSignal.LeftTurnCurvature	DINT
DestPoint	NDC8.LocalOrder.DestPoint	DINT

Figure 5: Some messages to be exchanged with the AGV

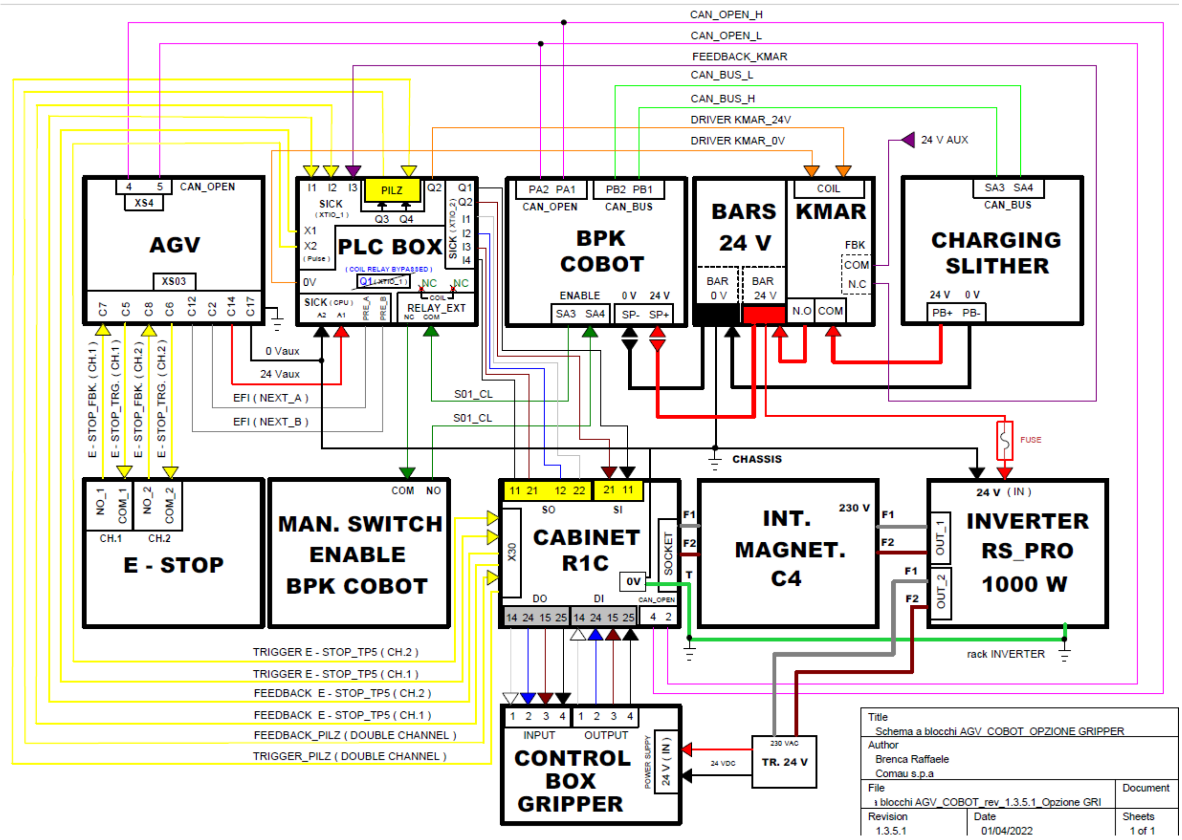


Figure 6: Block diagram of the mobile platform hardware components

2.3. AIC mobile manipulator

The mobile manipulator of AIC integrates the advantages of a robot arm, an automated guided vehicle and other smart capabilities. This platform (Figure 7) has already been presented in deliverable D1.3 and provides the following benefits:

- Eliminates Damage to Structures and Product.
- Increased Workplace Safety.
- Less Expensive than Fixed Automation Systems.
- Reduced Utility Costs.
- Increased Inventory Efficiency and Decreased Human Error.
- Reduced Labor Costs.

This platform will be deployed in the automotive setup at the Automotive Smart Factory (ASF). The ASF is a Competence Center specialized in advanced manufacturing, providing integral services for the implementation of Industry 4.0. The ASF has a combination of physical and virtual capabilities which makes it ideal for analysing the benefits of these technological advances. Specific technological topics that are physically tackled in the ASF include data mining, equipment and process monitoring, assets smart management, machine to machine communication, process simulation and control systems, digital quality management, human-machine interactions and new manufacturing training methods.

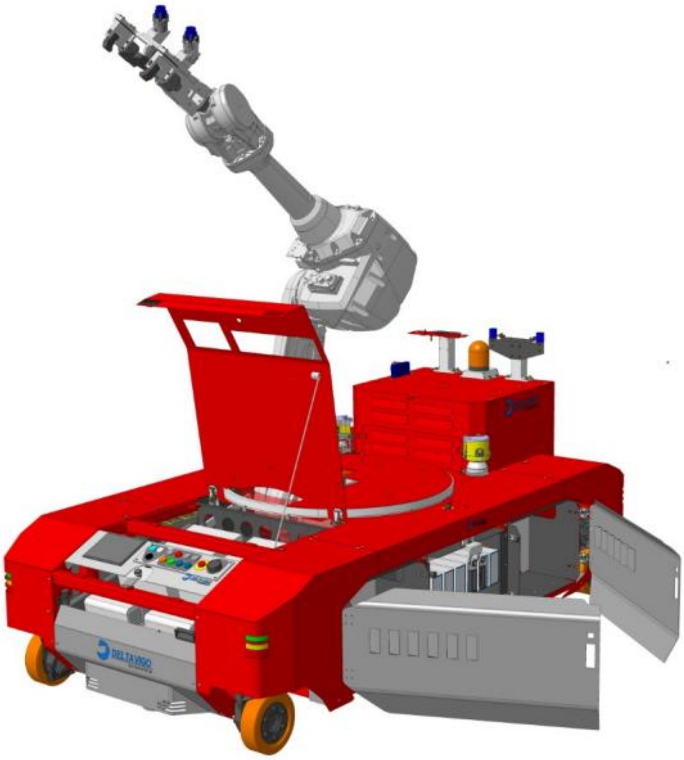


Figure 7: AIC mobile manipulator

The safety features of the AIC mobile platform are shown in Figure 8 and Table 1. The safety of the area around the AGV is fully guaranteed by the 6 laser scanner sensors. Four scanners are located on the underside, controlling the perimeter area, while the remaining two laser scanners ensure that no operators are located on top of the AGV. These two laser scanners are also used for lateral movement.

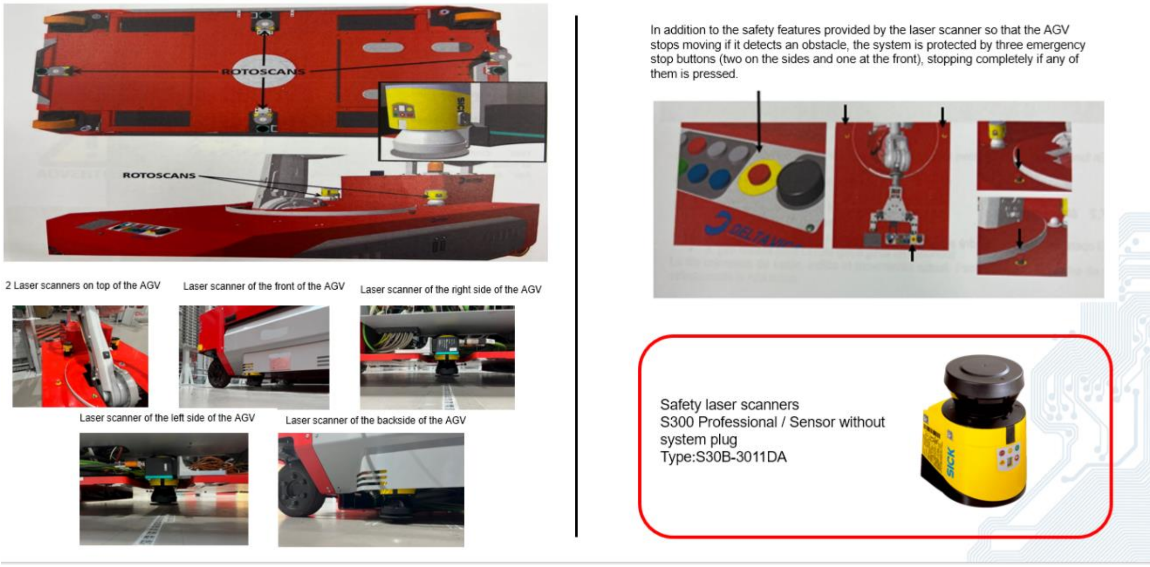


Figure 8: AIC mobile manipulator – Laser scanners

All hardware installed on the AIC platform is ROS compatible, allowing the integration of all technologies developed within ODIN.

Table 1: AIC mobile manipulator – Safety parameters

Features	
Model	Sensor without system plug
Application	Indoor
Protective field range	3 m
Warning field range	8 m (at 15% reflectivity)
Distance measuring range	30 m
Type of field set	Triple field sets
Number of field set	8
Number of fields	24
Number of monitoring cases	32[1)]
Scanning angle	270°
Resolution (can be configured)	30 mm, 40 mm, 50 mm, 70 mm, 150 mm
Angular resolution	0.5°
Response time	80 ms[2)]
Protective field supplement	100 mm
Number of multiple samplings	2 … 16, configurable
Delay of automatic reset	2 s … 60 s, configurable
Safety-related parameters	
Type	Type 3 (IEC 61496)
Safety integrity level	SIL2 (IEC 61508) SILCL2 (EN 62061)
Category	Category 3 (EN ISO 13849)
Performance level	PL d (EN ISO 13849)
PFH_D (mean probability of a dangerous failure per hour)	8.0×10^{-8} (EN ISO 13849)
T_M (mission time)	20 years (EN ISO 13849)
Safe state in the event of a fault	At least one OSSD in the OFF state

2.4. TECNALIA mobile manipulator

The TECNALIA platform is a mobile manipulator integrating two KUKA LBR iiwa robots [1]. The main advantages of the system are the following:

- Fully integrated hardware-software of robot arms and base.
- Easy to use by means of ROS framework.
- Omnidirectional base and considerable speed.

Figure 9: TECNALIA mobile manipulator

The mobile platform is equipped with 4x 1000W brushless mecanum wheels providing omnidirectional mobility. It provides 500 kg of payload and is able to move safely at 1 m/s speed. With the equipped batteries it has an autonomy around 6-8 hours.

Regarding the manipulators, there are two KUKA LBR iiwa 7 R800 arms mounted on top of the platform. Each manipulator has an 800 mm of maximum reach, 7 DOF and 7 kg of payload. For more details about the dimensions, capabilities, applied standards, and safety system architecture, please refer to Section 2.1.3 of D1.3.

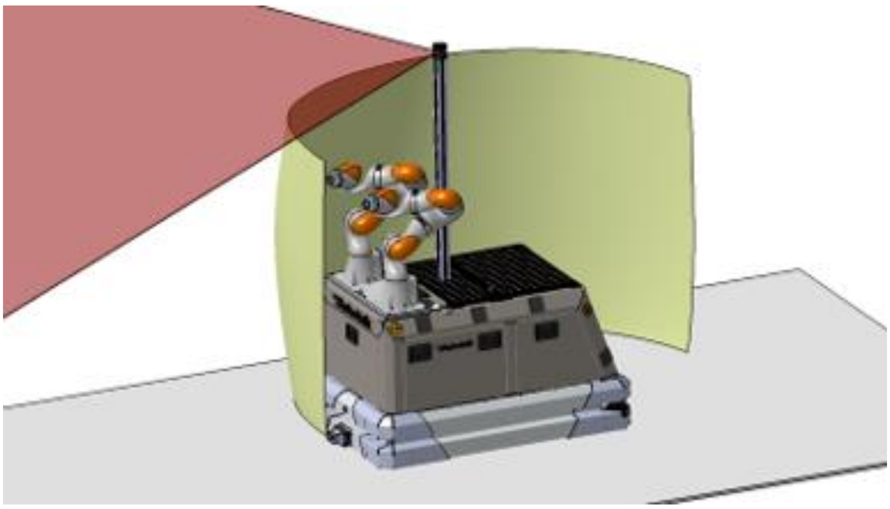


Figure 10: Mobile manipulator with the LIDAR mounted in a mast for Fan Cowl (FC) transportation

All the hardware of the platform is ROS compatible, thus, open enough for integrating the technology developed in the ODIN project. Task 2.1 of WP2 includes the development of 3D navigation technology, mainly for application in the Aeronautics Pilot. Additionally, the same navigation approach will also be deployed to the Automotive Pilot operation 2. A LIDAR sensor will be added on the mobile platform for the 3D navigation. As presented in Figure 10, due to requirements of the Fan Cowl transportation operation, the LIDAR must be installed on top of a mast in order to avoid interferences with the transported part.

3. RECONFIGURABLE ROBOT TOOLING

3.1. Overview

This section of the deliverable provides an overview of the current status of ODIN reconfigurable robot tooling module until M18 of the project. Additionally, the design principles for ODIN tools designing and selection are presented in this section of the document. The tools selected to be used in each pilot of ODIN for required robot tasks' execution will be presented in detail, in sections 5, 6 and 7.

3.2. Design principles for reconfigurable tooling prototypes

ODIN pilot cases involve the execution of human and robot tasks in Human-Robot Collaborative environments for different products' assembly. Robots are able to manipulate a big variety of parts in terms of geometry, weight and material thanks to reconfigurable tools. These tools have been designed taking into consideration the following principles:

- *Grasping/locking of the required parts during manipulation*

This aspect is centralized in the fail-proof grasping of the parts in order to ensure their safe manipulation by the robots involved in the ODIN pilot cases. The grasping/locking of parts depends on different characteristics, such as the part's weight, shape and edges. Regarding the automotive pilot grippers, mechanical connection parts such as steel pins have been selected and designed in order to sustain the required heavy loads. Furthermore, the grasping points on the manipulated parts have been selected so they can also sustain the required loads without interfering with the part's functionality. Regarding the white goods pilot, lighter parts are involved for manipulation and thus different type of tools (magnetic, vacuum and flexible) have been selected and designed. In the case of lighter parts (e.g. knobs, cardboards), no threat to the human operator is expected from the parts themselves. However, in the case of heavier parts (e.g. transformers and cooktops) a permanent magnet has been investigated taking into consideration safety aspects.

- *Ensure safety during Human-Robot coexistence and/or collaboration*

This principle is focused on the deployment of tools that are safe and appropriate for human robot collaborative applications. To ensure operators' safety during human robot collaboration, the installation of pressure-sensitive sensors peripherical to tools' body have been investigated (AIRSKIN technology) for the automotive pilot case. Furthermore, plastic covers with no sharp edges have been designed for some tools of the white goods pilot. Finally, tools' flanges and parts of their body which couldn't be placed in a plastic cover, have been designed in order to avoid sharp edges.

- *Versatility in terms of parts' manipulation*

Tools versatility is considered as the ability to grasp different components with small or no modification effort by the operator. This functionality is achieved thanks to the physical properties of the tools and the grasping mechanisms used (mechanical, electromagnetic and pneumatic). More specifically:

  - The automotive pilot's motor gripper achieves versatility since it is able to host different positions for gripper's pins. This can be exploited in order to manipulate different motor variants provided by the end user.
  - The white goods pilot's magnetic gripper achieves versatility by grasping a wide range of parts that have a ferromagnetic surface.
  - The white goods pilot's flexible gripper achieves versatility by grasping a wide range of small size parts with different geometric characteristics.
  - The white goods pilot's vacuum gripper achieves versatility by grasping low weight and flat surface parts (e.g. sheets, boxes) with various surface sizes due to its adjustable length.

- *Easy tool exchange and integration in a robotic cell*

The robotic cells involved in ODIN can easily accommodate/integrate more robot tools if needed through the use of tool stands as presented in Section 5.3 and 7.2. Furthermore, tool changing systems have been introduced based either on compressed air supply or mechanical solutions in order to easily change end-effectors depending on the needs of the pilots (Figure 11).

a) b)

Figure 11: Automated tool change solutions a) WINGMAN [25], b) SCHUNK SWK-110 [26]

- *Easy programming in terms of control*

The control of ODIN tools is based on Programmable Logic Controllers (PLCs) or safety reconfigurable relays. The PLC systems provide the control signals, for enabling the robot grippers and grasping the required parts. Also, they provide direct connection to the safety electro valves. PLC logic is reprogrammable to accommodate possible changes in the tooling actuators or even for new tools' integration.

a) b)

Figure 12: Safety control solutions a) Safety PLC, b) Safety reconfigurable relay

Further details regarding ODIN reconfigurable tools characteristics and designs per each pilot are presented in Sections 5, 6 and 7.

4. ROBOTIC PERCEPTION OF THE ENVIRONMENT, PROCESS AND HUMAN

4.1. Overview

All three ODIN Pilot Lines (Automotive, Aeronautic, and White Goods) require advanced perception capabilities for different tasks' execution but also to ensure the safety the HRC environments. This section describes the design and prototypical implementations of the perception skills required in these Pilot Lines, including:

- Object detection and pose estimation based on CAD models,
- Quality checks,
- Perception for screwing while moving operations,
- Object inspection of Aeronautics mechanical assemblies,
- Human body skeleton and human motion detection,
- Human detection and object localization.

These atomic perception modules are currently under development and as the integration process moves forward, their behaviour, architecture and interfaces might be adjusted to better suit the needs of the respective ODIN Pilots. The hardware components, including sensing devices, referenced in this section have been introduced in the previous deliverable D1.3 "ODIN hardware components architecture".

The integration of the perception modules in each ODIN Pilot Line is presented in the respective pilot section of this document. Additionally, a short overview of safety functions for robotic perception is presented in each pilot section. These safety functions are also described in detail in deliverable D5.1 "Report on the Risk Assessment performed in the design phase of the ODIN Pilot Lines".

4.2. Object pose estimation using CAD models

One of the perception skills required in all three ODIN Pilot Lines is the localization and 3D pose estimation of known parts and components in semi-structured shop floors.

The base software used for solving this task is the CADMatch module [2] by Roboception. This software relies on an object's CAD data and enables robotic systems to reliably detect, localize and pick said objects, fully independent of the object's position and orientation.

The architecture overview is shown in Figure 13. The input to the detection pipeline is a stereo image pair (rectified left and right images), together with disparity, disparity error and disparity confidence images.

Additionally, the CAD model of the part to be detected is required. This has to be as accurate as possible (ideally sub-millimeter precision) in order to achieved good detection accuracies. The CAD model is converted into a so-called template file which contains all data required for detecting the part.

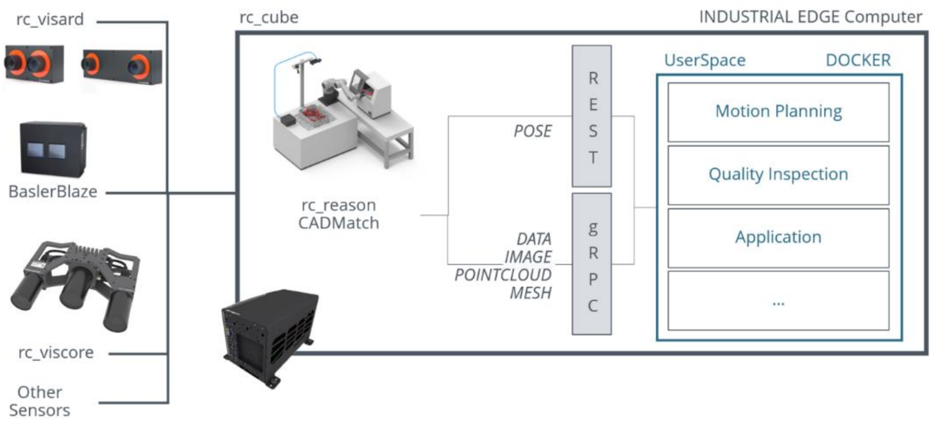


Figure 13: Architecture overview of the CADMatch software deployment

A detection request to the system needs to provide the ID (name) of the part to detect. The provided output includes a list of detected objects (matches) and optionally a list of collision-free grasps. Those grasps can be taught via an intuitive Web GUI interface (Figure 14).

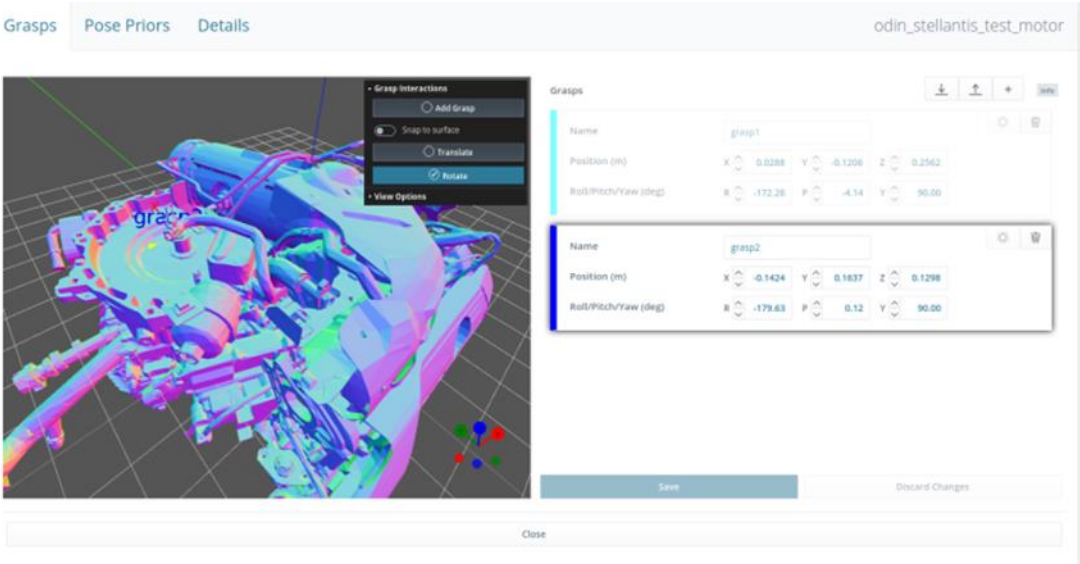


Figure 14: Grasp teaching Web interface (motor object from the Automotive Pilot)

The object detection is a two-stage process (Figure 15) consisting of:

- A prior estimation step, which computes an object pose prior based on the appearance of the object in the camera images using a deep learning approach
- A pose refinement step, which refines the prior pose by using the 3D point cloud and edges in the camera image.

The first stage leverages machine learning to generalize and make the detection robust against colour response of parts and lightning conditions (e.g. shop floor environments with artificial illumination and/or direct sunlight). On the other hand, the localization precision from the first stage is not accurate enough picking and placing of parts. The required precision is achieved with the second stage, which combines 3D and 2D data. The pose refinement pipeline (second stage) has been already successfully used in the THOMAS EU project [3].

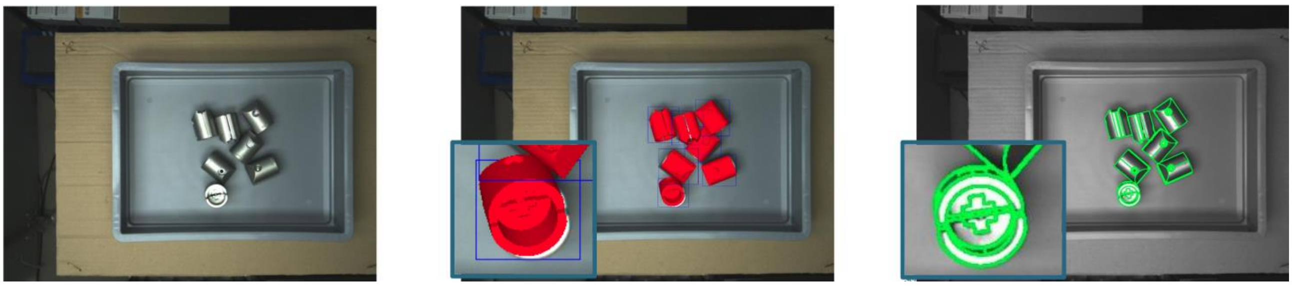


Figure 15: Stages in the CADMatch object detection pipeline: input image (left), detected pose priors (center), detected objects after pose refinement (right)

One of the main drawbacks of data-driven approach is the need for annotated training images. The training pipeline for the first detection stage runs entirely on simulation images and does not require any manual labelling. These images are generated in a photorealistic simulation environment (Figure 16). Since the salient feature for detection is the object geometry rather than its appearance, the simulation uses a large material library that makes the trained model independent of the object colour response in the camera image.

Figure 16: Sample training images generated in a photorealistic simulation environment

The simulation images are also used to estimate the achievable detection accuracy for each part. Basically, the simulation provides left and right images, which are fed to the stereo-matching algorithm, to produce a realistic 3D point cloud.

Figure 17: Simulation left and right stereo image pairs and reconstructed realistic point cloud

A sample detection result in the generated 3D point cloud from a simulation dataset is shown in Figure 18.

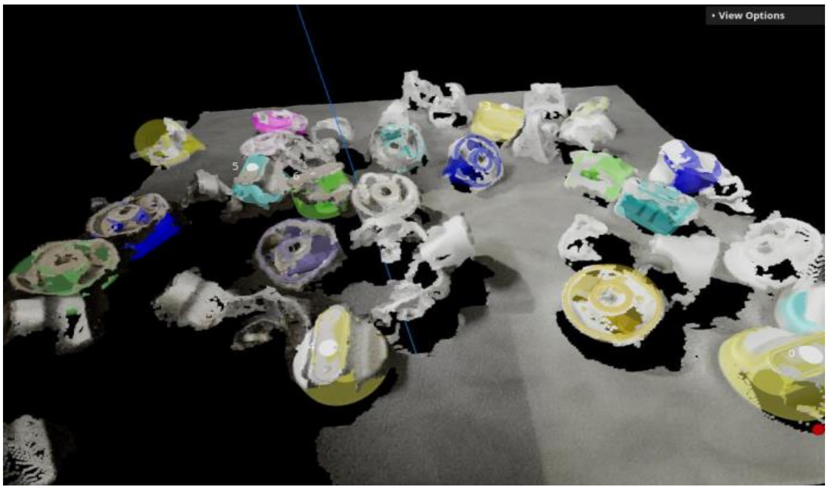


Figure 18: 3D visualization of the detection result in a simulation dataset (knob object from the White Goods Pilot).

The integration in the ODIN Pilot Lines also involves skills for context awareness (environment perception), such as using context information for object detection.

The software has been extended to use two different types of context information:

- Visual fiducials/markers (AprilTags [4]) for helping in the localization of regions of interest within the shop floor. These AprilTags can be strategically located in the shop floor or in the machines involved in the processes.
- Pose priors configured by the user as an indicative position and orientation for the object to detect. At detection time, these pose priors are then aligned to the actual object pose. This feature is recommended for applications where the object location is approximately known. Since the software does not need to search for objects in the whole image, the processing time is significantly reduced when pose priors are enabled.

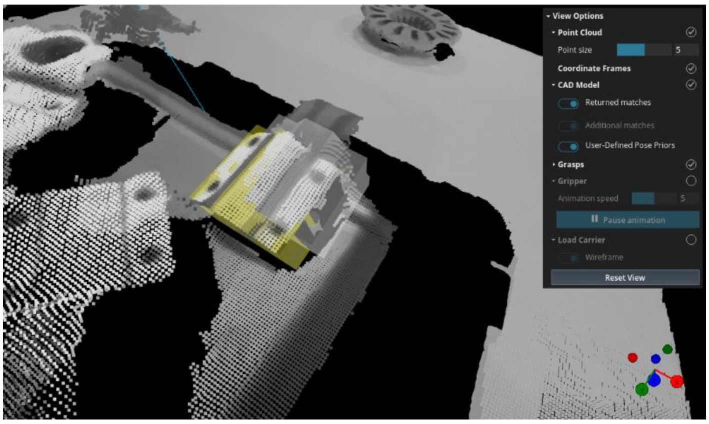


Figure 19: 3D visualization of an object detection with pose prior enabled

In addition to the rc_visard 3D stereo sensors (rc_visard65 and rc_visard160) [5], already introduced in D1.3, the detection performance of the pose estimation software have also been evaluated with the newly developed rc_viscore (Figure 20) [6].

The rc_viscore uses the same sensing principle (stereo vision) and consists of two 12 megapixels industrial cameras and the rc_randomdot projector. With 10 times the image resolution of the rc_visard, it extends the application domain of the rc_visard sensor family to smaller objects and larger measurement ranges. The rc_viscore is extrinsically factory calibrated (left to right camera) and works with the rc_cube in the same way as the rc_visard.

Figure 20: Stereo 3D vision sensors from Roboception tested with the object pose estimation software: rc_visard65 (left), rc_visard160 (center), rc_viscore (right)

The current design of the ODIN small-scale pilots includes robot-mounted cameras, in order to cover multiple workspaces with one single robot system. Since the rc_viscore is mostly suitable in a static setup, its application to the pilot lines will be considered only if a higher resolution camera is required during onsite testing.

4.3. Quality check

Quality checks and inspection tasks are common throughout all manufacturing processes in order to guarantee specification requirements and quality standards.

Automated visual inspection (AVI) systems can be used for quality or defect assessment. This perception skill is one of the core components of the Automotive business use-case AUTO-BUC-03 as defined in deliverable D1.1. The quality inspection is based on binary product classification. The initial prototype version of this quality inspection software receives an image and returns a single OK/NOK answer.

AI-based quality check solutions

The most common systems for OK/NOK quality checks use data-driven AI solutions. Basically, the user needs to capture images of good and defective products and assign each image an OK or NOK annotation (label).

After the labelling is done, the AI engine trains the recognition and correct assignment of the OK and NOK classification.

Sample companies that offer AI-based quality check systems are listed below:

- Google: Visual Inspection AI [7]
- Roboflow: Roboflow Annotate, Roboflow Deploy [8]
- MVTech: HALCON DL Toolkit [9]
- MoonVision: MoonVision AssemblyControl [10]
- Elunic: AI.SeeTM [11]

The MVTech HALCON solution has been selected as initial test system because of:

- Software availability (Roboception is a MVTech Image Acquisition Partner and DGH has already used it in production installations).
- Local deployment (no need to upload images to a remote cloud service).
- Ease of use.

The software comes as an external standalone tool for annotation, training, and evaluation of classification neural networks. For more advanced tasks, such as object detection, it can only be used for the annotation, but not the training or evaluation part. It offers a wizard-style guidance for the user with 6 steps: (1) choose project type (detection, classification, segmentation), (2) upload images, (3) annotate, (4) split training and validation datasets, (5) train, (6) evaluate.

Figure 21 shows an overview of the tool interface with a dataset of annotated images. Once all images are labelled correctly, the dataset is split in training, validation and test. The training dataset will be used for the actual optimisation of the network while the validation dataset informs of overfitting during the training. Finally, the test dataset is used for evaluation purposes.

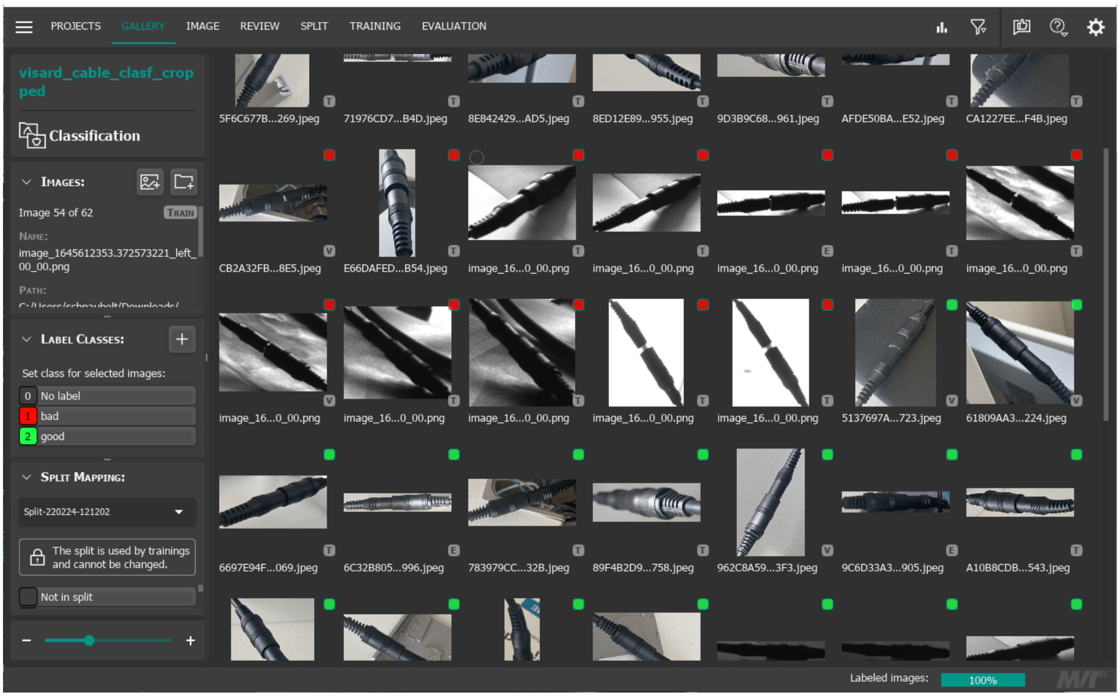


Figure 21: Gallery of input annotated images (test case for Automotive Pilot)

Some hyper parameters that can be customized before training process are:

- The pre-trained model to use to kick-start the training. MVTec offers some custom models ("Compact", "Enhanced") and some well-established open-source backbones (ResNet-50 [12], MobileNetV2).
- The input image size to the network.
- Whether to train the model using the GPU the CPU of the computed.

- Which augmentation methods to use in order to enlarge the number of training images. Currently these only contain basic augmentations, such as rotation, mirroring and brightness variations.

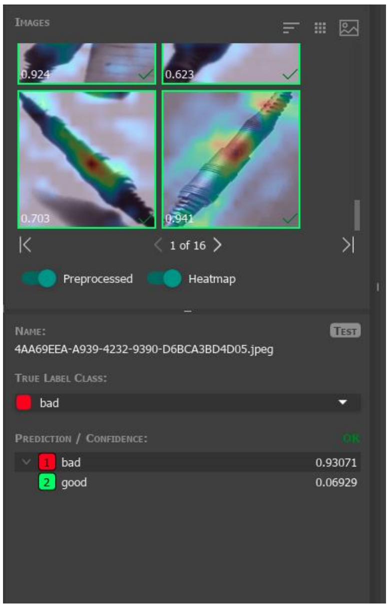


Figure 22: Heatmap visualization on correctly classified image

The training is evaluated using common metrics such as precision, recall, confusion matrix, etc. A rather advanced feature in the evaluation process is the heatmap, which gives visual hints about the parts of the image were decisive for the networks classification decision (Figure 22). This visualization approach may help dataset's optimization (e.g. crop images, remove background objects that confound the classification).

Figure 23 presents the test setup used for acquisition of datasets at DGH premises. In more details, this setup consists of:

- 1 x IDS UI-3360CP-C-HQ 2/3" Rev1 2048x1080 2D camera with optical configuration: 8mm and 25mm.
- 1 x 3D Photoneo S scanner.
- 1x UR10 CB3 robot.
- MVTech HALCON 21.11 software.

Figure 23: Setup for dataset generation

The vision systems are mounted on the robot arm to guarantee accessibility to the different inspection points. The train and validation datasets are generated by applying random displacements to the robot pose, up to 5mm in translation (X, Y, Z), and 3 degrees, in rotation (RX, RY, RZ). Also, the camera exposure is randomly modified within a small range. This procedure generates datasets similar to the ones that would be obtained in the actual production environment.

The generated datasets are equilibrated, containing approximately the same number of OK and NOK images. On the other hand, since all datasets were generated from the same engine, the scalability to different engines in production is still pending to be evaluated.

Initial results on some components on the Automotive motor are presented in Section 5.

Quality check based on CAD model

An alternative to AI-based binary inspection systems is based on the usage of an object's CAD model and match against the expected object pose. This can be implemented using the CADMatch software previously described with some interface extensions.

The quality check result is classified as NOK if:

- The object is not found at the expected location.
- The object is detected, but the deviation between expected and detected pose is larger than a configured threshold (both in position and orientation).

This approach works only for rigid parts and in cases where the part's expected pose can be uniquely defined. If the parts to be detected are not rigid bodies or their expected pose cannot be uniquely defined, it is recommended to use an AI-based solution as the one described in the previous section.

On the other hand, since the matching software also provides the actual object pose, this solution allows pose corrections in case the OK/NOK check fails. Such cases could be resolved directly by the robot system without manual intervention.

The input of the CADMatch solution is a stereo image pair (rectified left and right images), together with disparity, disparity error and disparity confidence images. Additionally, the CAD model of the part to detect and its expected pose are required (e.g., configured via the Web GUI). A detection request to the system needs to provide the ID (name) of the part to detect and the allowed deviation to the reference pose. The response contains a list of all requested parts, and, for each part:

- a boolean signal if the part is detected.
- a boolean signal if the check is ok (detected pose is within the allowed deviation).
- the part deviation to the reference pose (if detected).
- the detected pose of the part.

4.4. Perception for screwing while moving operations

The first prototype implementation of the detection and pose estimation for screwing while moving operation is a simplified version based on markers in order to test the complete control flow. More details about the perception for screwing while moving operation are presented in Section 5.4 since it is highly linked with the automotive pilot. After validating the control technology developed, the introduction of other perception modules will be studied.

4.5. Object inspection of Aeronautics mechanical assemblies

The perception module developed as part of the inspection system for the use-case AERO-BUC-03 is based on the specifications introduced in Deliverable D1.2 "Specification Analysis for ODIN Core Enabling Technologies" in the requirement AERO-R-09. In more details, these specifications are the following:

1. Have an agile and accurate way of performing the extrinsic calibration of the 3D sensor used for the reconstruction.
2. Perform an initial positioning of the sensor in respect to the scene or the part, that allows to start the scanning operation.
3. Plan the trajectories of the robot for the correct acquisition of the views for the 3D reconstruction.

4. Generate a 3D reconstruction of the inspected part in an online and efficient manner.
5. Develop and integrate methods for efficient alignment of the 3D models.
6. Segment the different elements of the part/model so that the inspection results can be communicated to the operator in a useful way.

Figure 24 presents the conceptual diagram with the different blocks that are being developed in order to fulfil the previously documented specifications. The inspection system will create a 3D reference model of a part which is classified as correct, and that reference model will be used to be checked against new scans of the target object to be inspected. The objective is to have an easy-to-configure system that is able to correctly detect presence/absence of parts being mounted into the target object, and to verify that the mounting position (and orientation) is according to specification. Instead of relying on ad-hoc rules to check for the large number of possible components, the easiness of use by providing a teaching procedure is targeted. Thus, adding new components to be checked does not require additional programming, but just the generation of a new reference model.

The current focus of the development is on the scanning process of the inspection object, which corresponds to the block “Online multi-view fusion” in the diagram. The main target is for the system to be able to produce a full reconstruction of the whole object to be inspected. There are different challenges for the model-based inspection process such as:

- the large size of the object.
- the required high resolution in relation to the total size of the object.
- the need to have a system that is able to construct the representation online, i.e. the reconstruction needs to be produced while doing the scan so that it does not have a big impact on the total time, and allows for online correction for a consistent model.

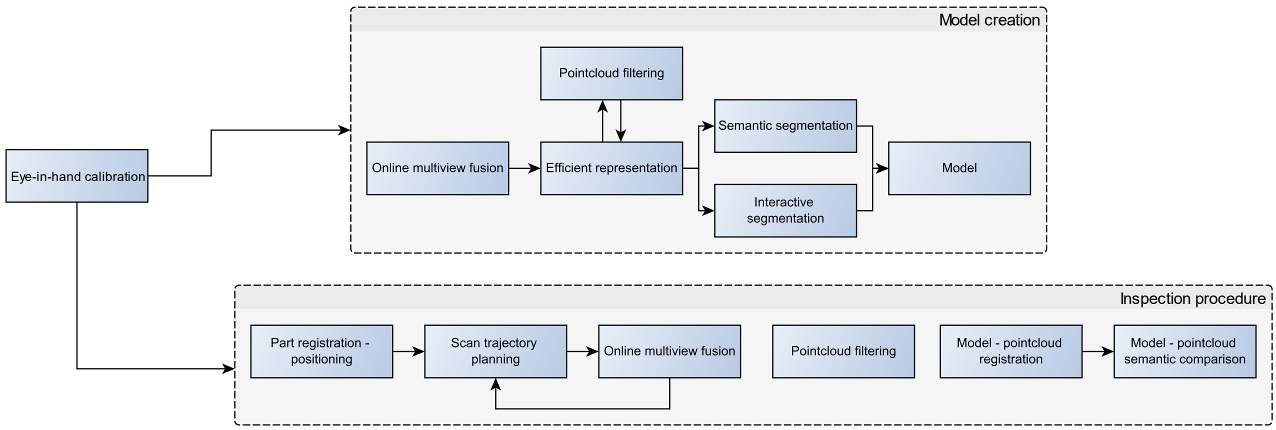


Figure 24: Conceptual diagram for model-based inspection

A 3D vision sensor has been installed to a robot arm in an eye-in-hand configuration for the multi-view fusion problem. This setup allows to simulate the same scan movements that would be realized in the real scenario. The left picture in Figure 25 shows the camera mounted on a Fanuc CR-7iA/L robot used for the development phase and the right picture shows the sample workspace used for reconstruction.

Figure 25: 3D vision sensor in eye-in-hand configuration (left) and workspace setup for reconstruction (right)

A Photoneo MotionCam-3D sensor is used for capturing the required 3D images [27]. On the one hand this sensor has a good performance in terms of accuracy of the measurements and density of the point cloud produced. On the other hand, current sensors are based on structured light and require a static scene to produce the point clouds. Structured light sensors usually project a number of patterns (can be from 8 to 32 patterns) and capture how the scene's geometry affects the projection of the patterns. Based on the deformation of the patterns, they produce a 3D point cloud. This approach requires the scene to be completely static while the set of patterns is being projected and captured. In practice that means that both the camera and the scene must be static. This might be impractical when scanning large scene or objects, as the robot must pause the movement for every capture.

The Photoneo MotionCam-3D offers two capture modes. The first mode named the scanner mode works as a standard structured light sensor, with a sequence of patterns being projected and captured. But it also offers a camera mode, in which a single pattern can be projected in continuous mode, allowing for the capture of static scenes, or in the case of the inspection system, allowing for a continuous scanning movement. As shown in the sensor's datasheet in Table 2, the camera mode has reduced accuracy. The absolute accuracy for the depth measurement in scanner mode (static capture) is 0.150 mm, and drops to 0.300 mm in scanner mode (i.e. capture while moving), while the repeatability of the measurements drops from 0.050 mm to 0.100 mm.

Table 2: Photoneo MotionCam-3D S datasheet

Parameter	Value
Scanning range	366-558 mm
Camera mode	
Point Size	0.37 mm @z = 442 mm
Accuracy	< 0.300 mm
Temporal Noise	< 0.100 mm
Scanner mode	
Point Size	0.25 mm @z = 442 mm
Accuracy	< 0.150 mm
Temporal Noise	< 0.050 mm
General Information	
Depth map resolution (static mode)	1680 x 1200
Depth map resolution (dynamic mode)	1120 x 800
Maximum FPS	20 fps
Data acquisition time	10 ms
Maximum object / camera speed	40 m/s
3D point throughput	15 million points per second

After the successful integration and calibration of the camera, several strategies for multi-view fusion have been developed and evaluated. The challenge of this step is on the fusion of overlapping point clouds that convey noise, both from the sensor's measurement, but also from the sensor's positioning which comes from the pose declared by the robot (including also noise due to the eye-in-hand calibration). A common approach is to use a representation named Signed Distance Fields (SDF). The SDF is an implicit surface representation. It uses a voxel-like description, but instead of just describing the occupancy of a voxel, each voxel contains the distance to the closest surface. It allows the efficient integration of new measurements, smoothing out the noise over observations and efficient generation of a mesh representation.

The two steps of online reconstruction example using the voxblox library [13] is presented in Figure 26. Voxblox is a TSDF library that runs using only the CPU of the corresponding computer. The white point cloud represents a single capture of the sensor, which only corresponds to a small volume of the scanning area. The red point cloud is the TSDF representation fusing the different views and the purple surface presentes the resulting mesh produced from the TSDF.

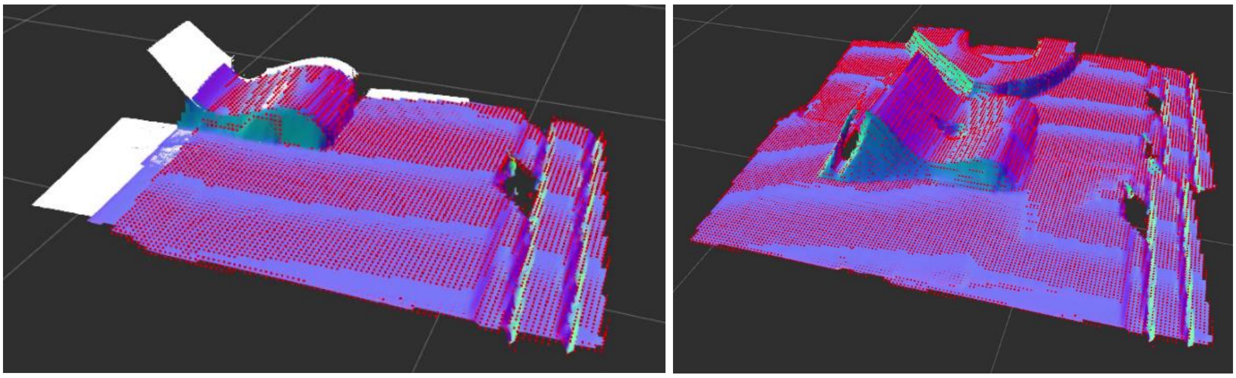


Figure 26: Initial reconstruction step (left) and final reconstruction visualization (right)

4.6. Human body skeleton and human motion detection

The main hardware of the perception module developed for human body skeleton and human motion detection is the Microsoft Kinect V2, which has three internal cameras, namely RGB Camera, Depth Sensor, and IR Emitters. The RGB camera is used to obtain high-definition colour images in the field of view of the camera, while IR emitters actively project modulated near-infrared light. The infrared ray that shines on the object in the field of view will be reflected. The infrared camera receives the reflected infrared ray, measures the depth, and calculates the time difference of the light. Then, the depth of the object can be obtained based on the above information.

The Kinect V2 has 6 basic data sources, which are RGB image, infrared image, depth image, skeleton image, character index binary map, and sound source. For the perception module, depth images are treated as an acquisition input. It has a resolution of 512*424 and is capable of capturing at a frame rate of 30 fps, while having an effective viewing range of 0.5 to 4.5 meters. By using a deep learning model based on 3D (dimensional) convolutional neural network (CNN) [14], 3D human coordinates can be extracted from the input depth image. Embedded functions of Kinect V2 used for capturing skeleton images can be an option, but with less accuracy compared to the neural network model.

Following the success of deep learning methods in several computer vision tasks, deep recurrent neural networks (RNN) are developed to model human motion with the goal of learning to perform tasks such as short-term motion prediction to detect human motion [15]. Here, it is observed that the dynamic time slices of human motion are crucial to the accuracy of detection because using the short-term motion of a human operator as a detection metric is much more accurate than the motion of a particular frame of a picture.

In the developed human motion detection module, human skeleton data is required as the main input, where the most likely future 3D poses of a person given their past motion can be predicted, as shown in Figure 27. The workflow starts by the training of action-specific models using a sequence-to-sequence architecture with sampling-based loss. Then, short-term motion prediction as the search for a function that maps an input sequence (conditioning ground truth) to an output (predicted) sequence can be addressed and realised. The next step is to use residual connections to model prior knowledge about the statistics of human motion. During the training process, the benefits of training the proposed architecture on the entire human 3.6M dataset can be qualified, as opposed to the built action-specific models. Here, both supervised and unsupervised variants are considered. The supervised variant enhances the input to the model by concatenating one-hot vectors with the 15 action classes. While the unsupervised variant does not use one-hot input during training nor prediction. In experiments, the network is trained to minimise the prediction error over the next 400 milliseconds. Therefore, the model is trained by a large dataset of human motion and then the final results of human motion detection can be obtained, as shown in Figure 28.

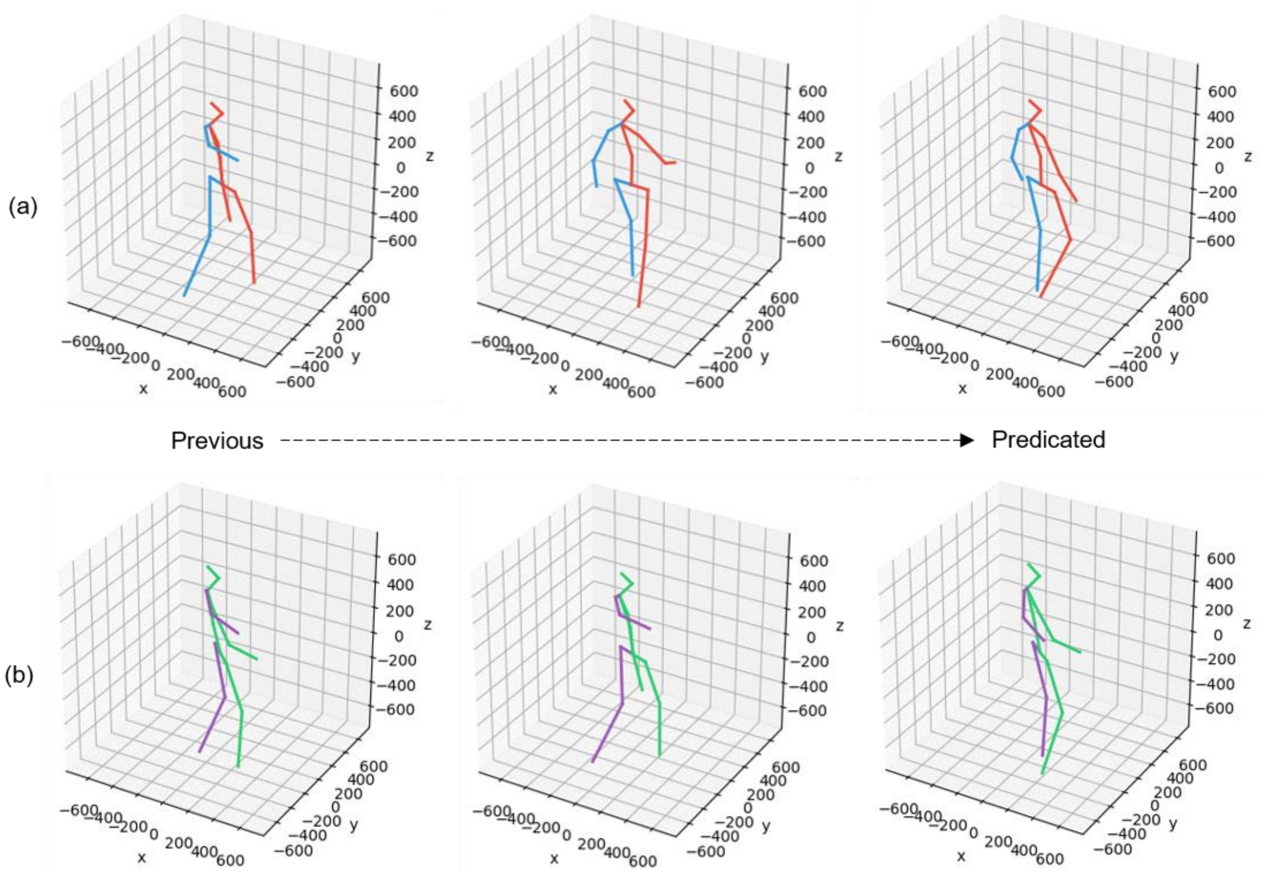


Figure 27: Movement of the human skeleton prediction under two time series [15]

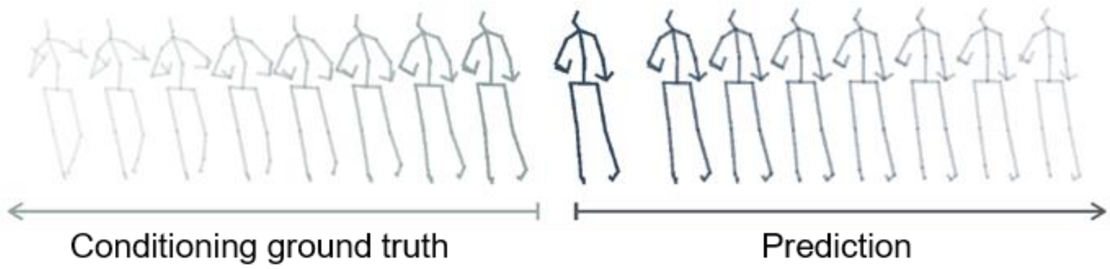


Figure 28: The results of human motion detection (ground truth passed to the network is shown in grey, and short-term motion predictions are shown in darker color) [15].

4.7. Human detection and object localization

Using augmented environments can improve operator's capabilities by providing up-to-date information on the work cell's status, helping operator with his/her task or warning operators in case of danger when operating with the robot. For such systems, it is important to have a robust monitoring system for the environment. In ODIN, as RGBD-based approach for the task of robot cell monitoring is used. The setup consists of one or multiple RGBD sensors, installed on top of the work cell. In current experiments, Azure Kinect sensors are used since they provide a good balance between price and quality of depth/RGB images, as well as user-friendly APIs for processing data and syncing multiple devices. RGB images are calibrated to produce perspective transform to the perpendicular view of the cell. Depth data from sensors is calibrated to a single coordinate system (generally robot coordinate system). The monitoring provides the following functions:

- *UI control with projector-based interface.*

  The projector-based interface provides a cheaper alternative to mixed reality headsets. To detect interactions with the UI, the areas of interactive elements are monitored for change in depth data using RGBD sensor. When user puts his hand over the UI element, the depth in the area changes, and a signal that the element is being interacted with is sent. To improve robustness of the system, camera also takes RGB snapshot of the element area and tries to detect hand landmarks. The interaction signal is only sent when these hand landmarks align with the button area. Hand landmarks can also be checked for a specific hand gesture position to further decrease chance of unintentional button press. The module uses Google's mediapipe hand detection model, which has good accuracy and real-time performance even on CPU hardware.

- *Detection of surface of mobile UI interface*

  Projector-based interface can be also used with surfaces that can be moved around the work cell. To detect this surface, an Aruco marker is placed in the corner which can be detected from RGB data of the sensor. Surface corners can be found by either putting multiple markers in the corners of the surface or by using one marker and its size relative to the size of the surface. Additionally, OpenCV's implementation of Aruco marker detection is used [16].

- *Safety Border monitoring with depth sensor*

  RGBD sensor is calibrated against the robot's joint coordinates. A virtual border is generated based on the robot joints' positions. Similarly to UI interaction detection, the depth values along that border are monitored against template depth image. In case that a change in depth values is detected, a signal is sent to warn user for possible danger.

5. AUTOMOTIVE PILOT

5.1. Overview

The Automotive pilot case is focused on the motor and gearbox assembly produced by STELLANTIS. There are three main operations involved (Figure 29):

1. the motor & gearbox assembly,
2. the additional parts assembly,
3. the quality check.

For the first operation, a COMAU AURA high payload collaborative robot is selected to safely pick and place the motor on a conveyor using a custom reconfigurable motor gripper. Also, the AURA robot, is responsible for transporting a gearbox in the proximity of the motor using a custom gearbox gripper. At that point, a human operator manually guides the AURA robot, so that the gearbox aligns with the motor and also performs the assembly of these two main parts. During the second operation, a human operator places some additional parts on the assembly, and after this the TECNALIA dual arm mobile robot performs a screwing while moving task to screw the additional parts on the overall assembly. During the third operation, the COMAU mobile robot performs the quality inspection and in the case of any support/confirmation needed a human operator is allocated to support the inspection tasks. Based on the definition of the automotive pilot line, the Automotive pilot layout has been consolidated as presented in Figure 29 in order to facilitate the three main operations involved in this pilot.

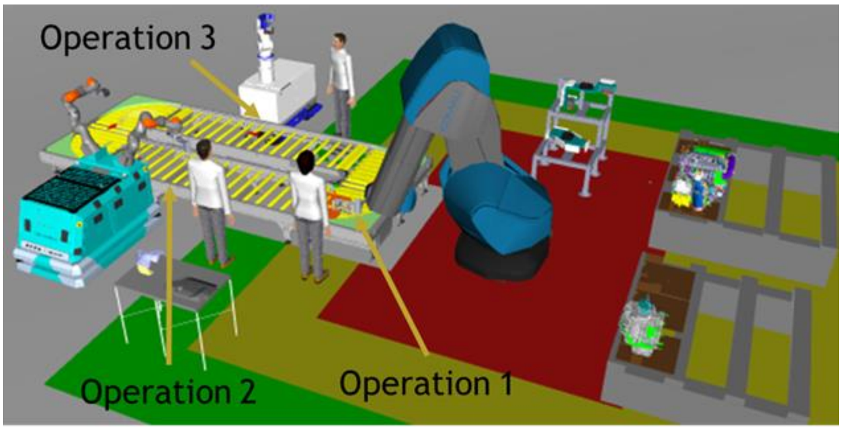


Figure 29: Automotive pilot overview

5.2. Autonomous mobile and robotic manipulators

This section focuses on the usage of autonomous mobile and robotic manipulators in the Automotive pilot as described in Section 2.

COMAU mobile manipulator

The COMAU mobile platform plays a major role during the third operation of the Automotive Pilot (Figure 29) which is focused on the inspection of the Motor and Gearbox assembly. This process takes place in motion on the conveyor, generating some challenges in the control of the platform and safeguarding of the operation.

In order to perform the inspection task, the mobile platform will be equipped with a camera system that allows the visual assessment of the kitting process. Section 5.4 provides an overview on the inspection task focusing on the object perception. Moreover, a specific path for the AGV will be programmed alongside the conveyor (using the tools mentioned above) and the mobile platform will move along this path with same speed as the conveyor.

During this operation, the robotic arm mounted on top of the AGV will be extended beyond the perimeter of the AGV itself (Figure 30), thus posing an additional risk. This comes from the fact that only the perimeter of the AGV is safeguarded by the laser scanners on board and if the arm is extended outside AGV's perimeter then there's not yet a system installed on the AGV that will safeguard this risk.

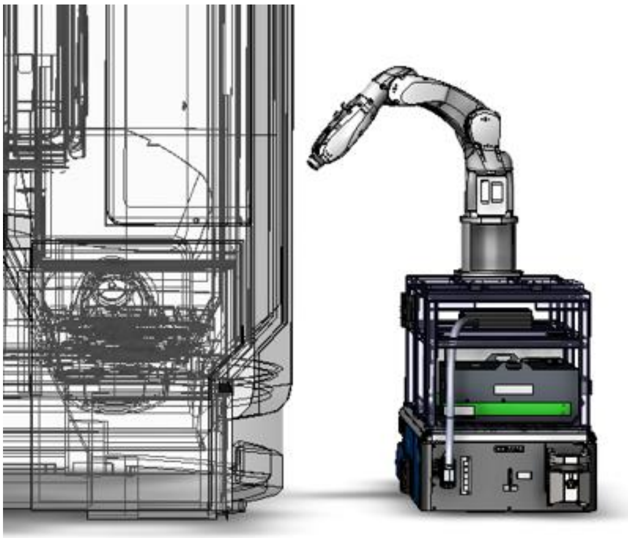


Figure 30: Robot arm extended outside the AGV perimeter

It is important to note a distinction between the simultaneous movement of AGV and Cobot, and the alternate movement of one or the other. In fact, since the robot arm is collaborative, it is able to work without fences or access sensors while the AGV stands still. The same situation applies for the AGV, which includes laser scanners for navigating and for safe monitoring of the area around, so that its perimeter cannot crash with an operator. However, when both AGV and robot arm move simultaneously, the operation needs to be safeguarded. As an example, it can be imagined the situation in which the arm is fully extended to one side and an operator stands on the same side, 30 cm from the platform. In this case, the laser scanners will slow down the platform and this will reduce the scanned field itself. If no measures are taken, the robot arm will crash with the operator and the AGV will need a certain space in order to stop completely.

To safeguard this operation is thus necessary to take into account the whole process. In fact, when the arm is extended over the conveyor, this poses no risk to the operator, since he/she cannot be intercepted by the extended arm. Section 2.2 provides a concept safety system that will allow the platform to extend the arm over the AGV's perimeter only if it is located close to the conveyor.

Lastly, another point to be aware of is that the AGV, for its nature, is a machine that performs very well in navigating an environment and going from one point to the other, however it is not made to follow a path precisely and with an accurate set speed. In order to ensure that the Agile 1500 is able to keep up with the requirements of the task, several tests will be performed and the drive control PID parameters will be adjusted accordingly.

<u>TECNALIA mobile manipulator</u>

The mobile manipulator used in the 2nd operation of the Automotive pilot is the same model with the one which is used in the Aeronautics pilot. TECNALIA will try to use the same hardware for both use case, demonstrating in this way the versatility of the developed technology. More details about the TECNALIA mobile platform are presented in Section 2.4 of this document. Additional details can be found in Section 2.1.3 of deliverable D1.3.

<u>AIC mobile manipulator</u>

The mobile manipulator embedded in the AIC mobile platform will be deployed to the AUTO-BUC-03 use-case (quality inspection). AIC is working to standardize the design, manufacturing and validation of this device to demonstrate the ODIN objectives.

The first version of the AIC mobile manipulator (Figure 31) was designed to support the logistic and traceability processes using traditional materials. AIC, DGH and TECNALIA are working on an updated version focusing on:

- Lightweight materials
- Updated and collaborative design
- Multifunction capabilities
- Sensor embedded (Figure 32)

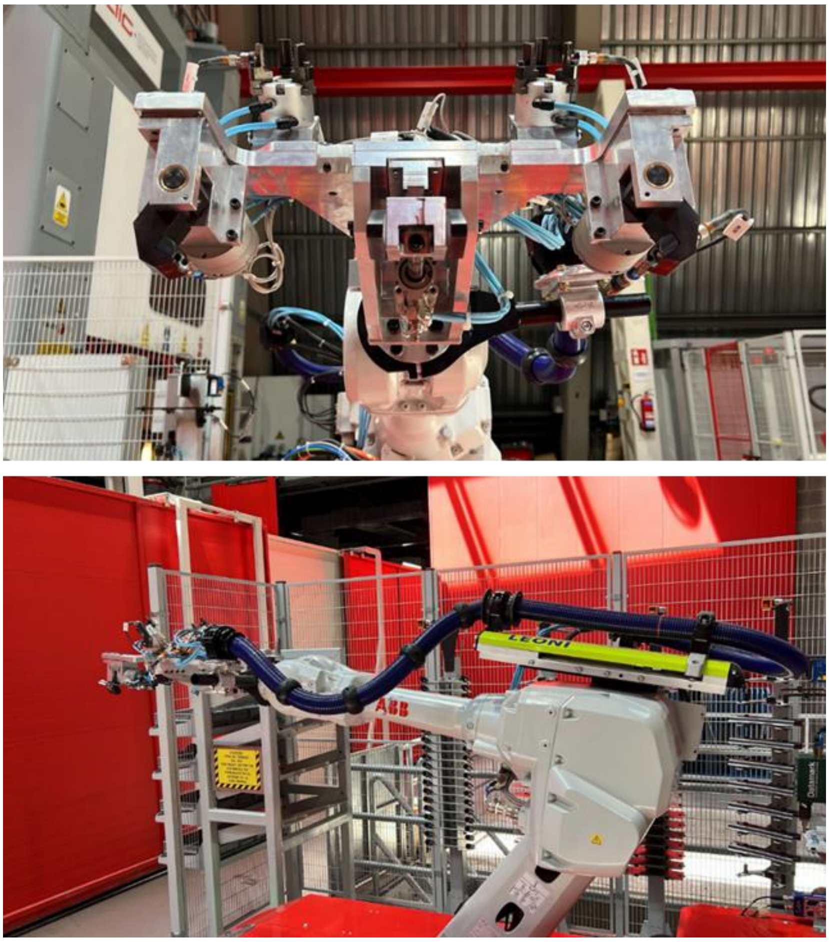


Figure 31: Current version of the AIC mobile manipulator

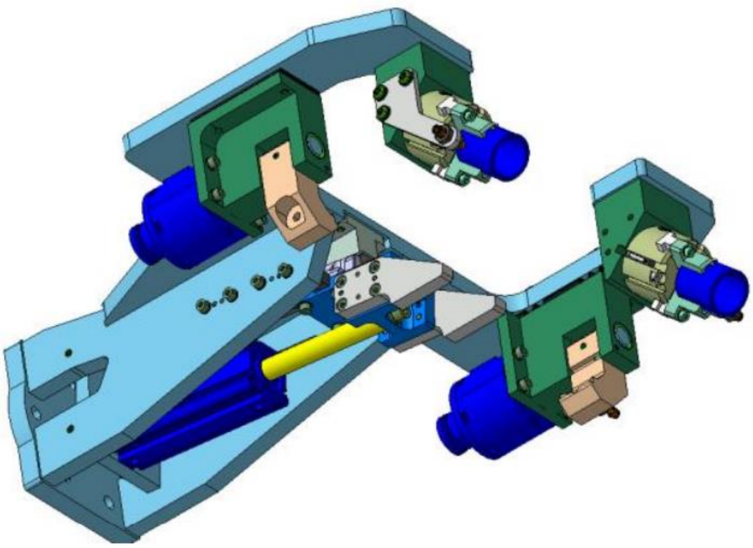


Figure 32: Design of the AIC mobile platform tooling for the quality inspection task

5.3. Reconfigurable robot tooling

This section presents the initial prototype of the tools designed for the Automotive pilot.

Gripper for motor manipulation

The robot gripper designed for motor's manipulation is presented in Figure 33.

a) b)

Figure 33: Motor gripper a) View 1, b) View 2

This reconfigurable gripper consists of the following components:

- Tool changer (Figure 34)

  This component has been installed on the top side of the motor gripper's main body in order to be attached at the robot's end effector.

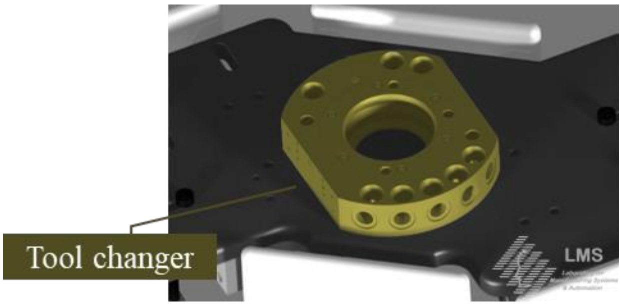


Figure 34: Motor gripper's tool changer

- Custom designed body for subcomponents installation (Figure 35)

  This is the main component of the motor's gripper and all the other components of the gripper are installed on top of that. In terms of reconfigurability of the gripper, the design of this component has been based on the manipulation of two different motor variants. In order to manipulate different variants, the only action required is to change the location of the linear actuators and pins.

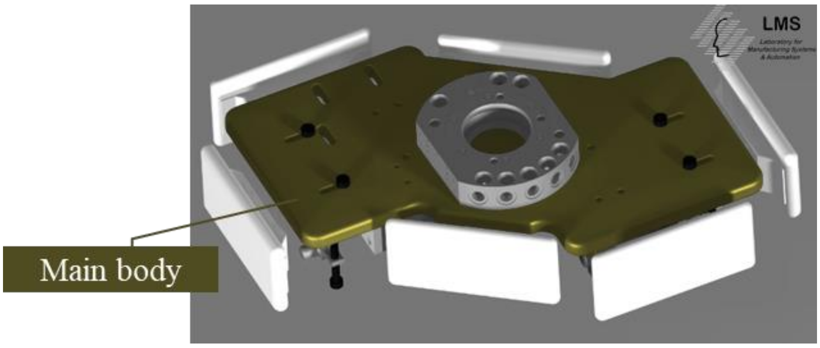


Figure 35: Motor gripper's main body

- Linear actuators for motor's grasping (Figure 36)

The motor gripper grasps the motor by inserting the metallic pins to the respective motor geometrical points. The motor gripper consists of 4 pneumatic linear actuators and the motion of each pin is based on two pneumatic actuators. The motion of each installed actuator is presented in Figure 36 through the back arrows.

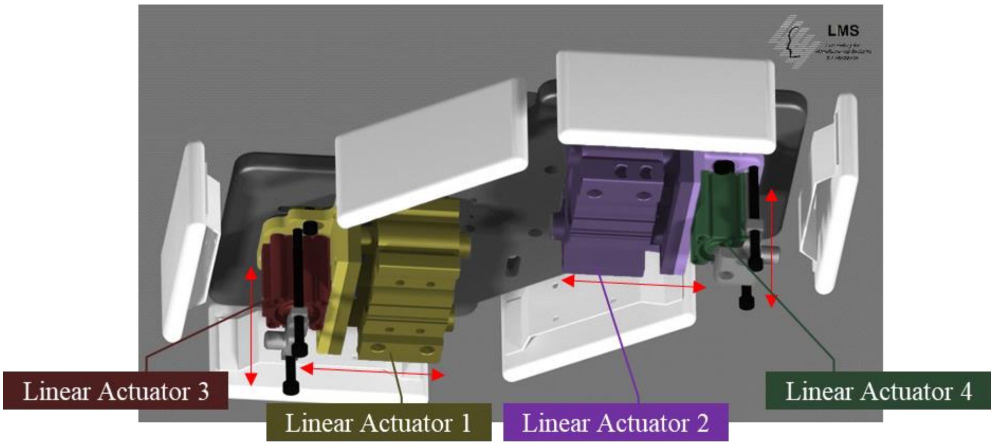


Figure 36: Motor gripper's linear actuators

- Custom designed pins (Figure 37)

Steel pins have been included in order to better distribute the required payload and cover the needs of the automotive case. The number and position of these pins can be easily changed in order to adapt in different motor variations. Furthermore, two lock pins have been introduced in order to ensure the safe locking of the gripper in the motor's grasping points.

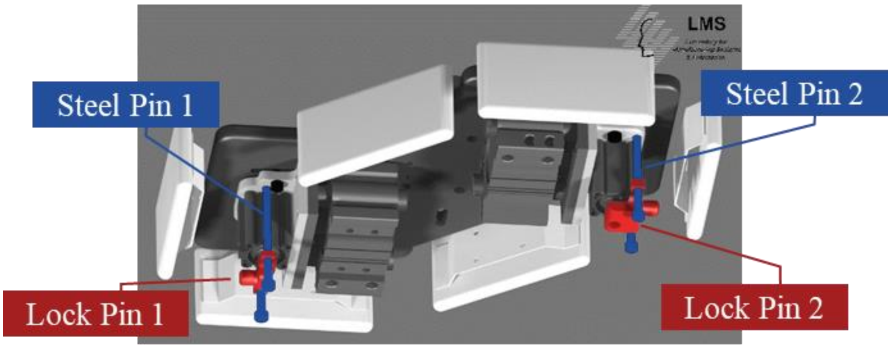


Figure 37: Motor gripper's pins

- Inductive sensors [17] (Figure 38)

Inductive sensors will be considered on this gripper in order to provide feedback about the success of the grasping process.

Figure 38: Safety inductive proximity sensor

- Pressure-sensitive sensors (AIRSKINS) [18] (Figure 39)

Pressure sensors AIRSKINS will be considered on this gripper to avoid collisions with obstacles and the human operators. In case of collision with operators, electrical signals are sent to the robot controller to stop robot's motion.

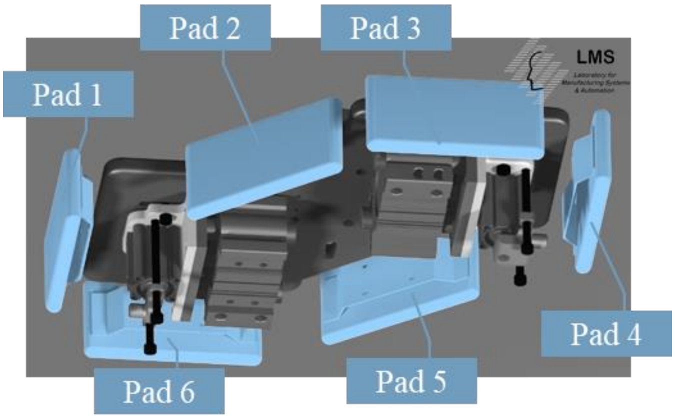


Figure 39: Motor gripper's AIRSKINS pads

<u>Gripper for gearbox manipulation</u>

The robot tool designed for gearbox manipulation is visualized in Figure 40.

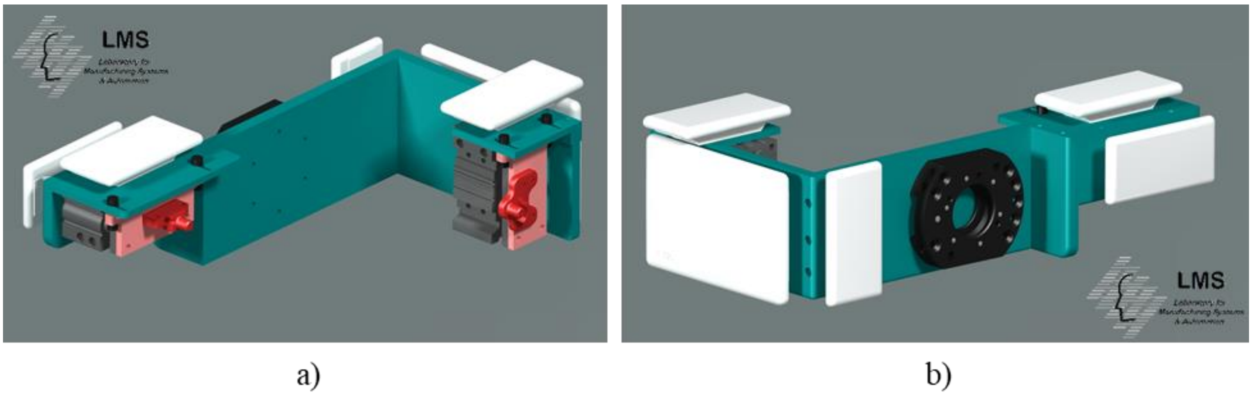


Figure 40: Gearbox gripper a) View 1, b) View 2

The gearbox gripper consists of the following components:

- Tool changer (Figure 41)

This component has been installed on the top side of this gripper's main body in order to be attached at the robot's end effector.

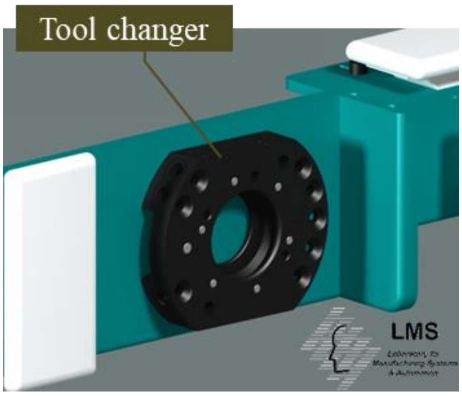


Figure 41: Gearbox gripper's tool changer

- Custom designed body for subcomponents installation (Figure 42)

This is the main component of the gearbox's gripper because all the required components of the gripper for the safety concept and gearbox' grasping are installed on it (Figure 42).

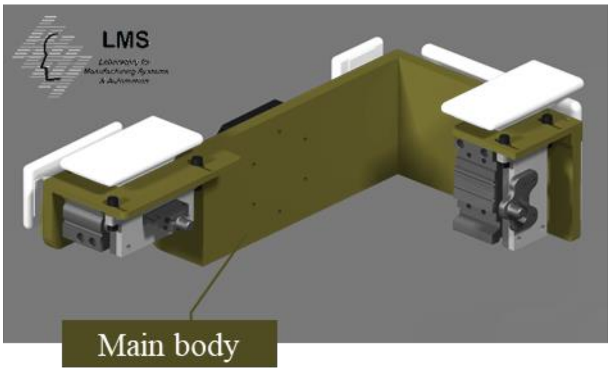


Figure 42: Gearbox gripper's main body

- Linear actuators for gearbox's grasping (Figure 43)

Gearbox's grasping is achieved through 2 custom designed pins (Figure 44) installed on two linear pneumatic actuators (Figure 43) placed on the main body of the tool. The black arrows in Figure 43 present the motion of each installed actuator.

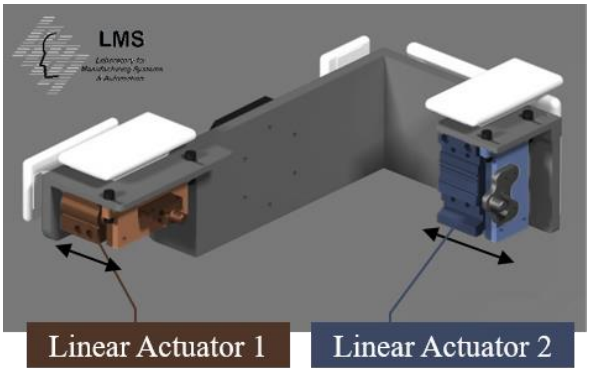


Figure 43: Gearbox gripper's linear actuators

- Custom designed pins (Figure 44)

Following the same methodology with the motor gripper, steel pins have been installed on the gearbox gripper in order to better distribute the required payload and cover the needs of the automotive case. Furthermore, two lock pins have been designed to ensure the safe locking of the gripper in the gearbox's grasping points.

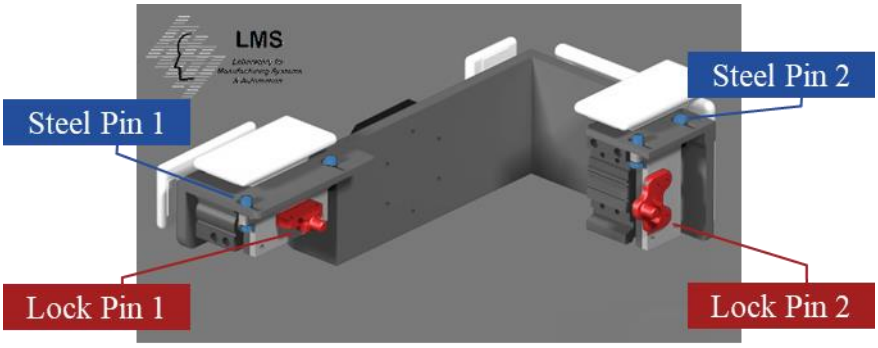


Figure 44: Gearbox gripper's pins

- Pressure-sensitive sensors (AIRSKIN) (Figure 45)

Following the same methodology with the gearbox gripper, 5 pressure sensitive sensors will be considered on this gripper to increase the safety in the HRC environment and stop robot's motion in case of tool's collision with the operator.

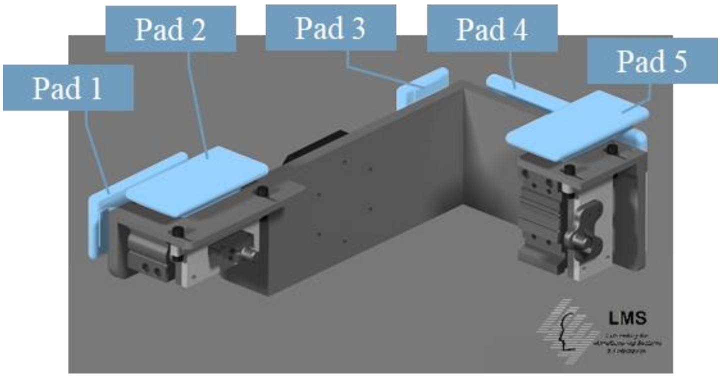


Figure 45: Gearbox gripper's AIRSKINS pads

<u>Tool changer system</u>

The Schunk SWK 110 tool changer system (Figure 46) has been selected to perform the automatic tool changing, by the COMAU AURA robot, in order to pick and place the motor and gearbox. The tool changer system consists of two different parts: a robot part and a tool part. The system and its parts are depicted in Figure 46.

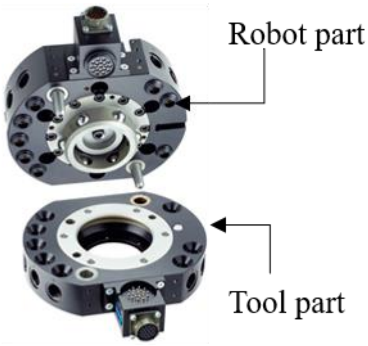


Figure 46: Schunk SWK 110 tool changer system

<u>Tool for screwing while moving task</u>

The description of the tooling for the screwing while moving task (AUTO-BUC-02) is included in the next section, together with the perception solution prototype as these components are deeply connected. By the time the visual servoing technology is ready, a screwing machine will be integrated on the robot in order to face the screwing operation.

The most likely candidate tool for the screwing operation is an ESTIC cordless Handheld Nutrunner [28], since has been used in previous projects by the partners and provides interesting features as the wireless operation (see Figure 47).

Figure 47: ESTIC coordless Handheld Nutrunner

5.4. Process perception

This section presents the use of perception modules in the Automotive pilot as described in Section 4.

Object pose estimation using CAD models

The CADMatch 3D pose estimation module will be integrated in the Automotive business use-case AUTO-BUC-01 for motor and gearbox assembly and potentially in AUTO-BUC-02 for additional parts assembly.

The detection will be performed on the rc_cube platform from ROBOCEPTION and will use a robot-mounted rc_visard sensor as sensing device. For AUTO-BUC-01, motors and gearboxes are located on separate pallets and the sensor will have a top-down view on them. The object pose is expected to be approximately known, and the use of pose priors is planned (Figure 48). All tests so far have been conducted in a simulation environment.

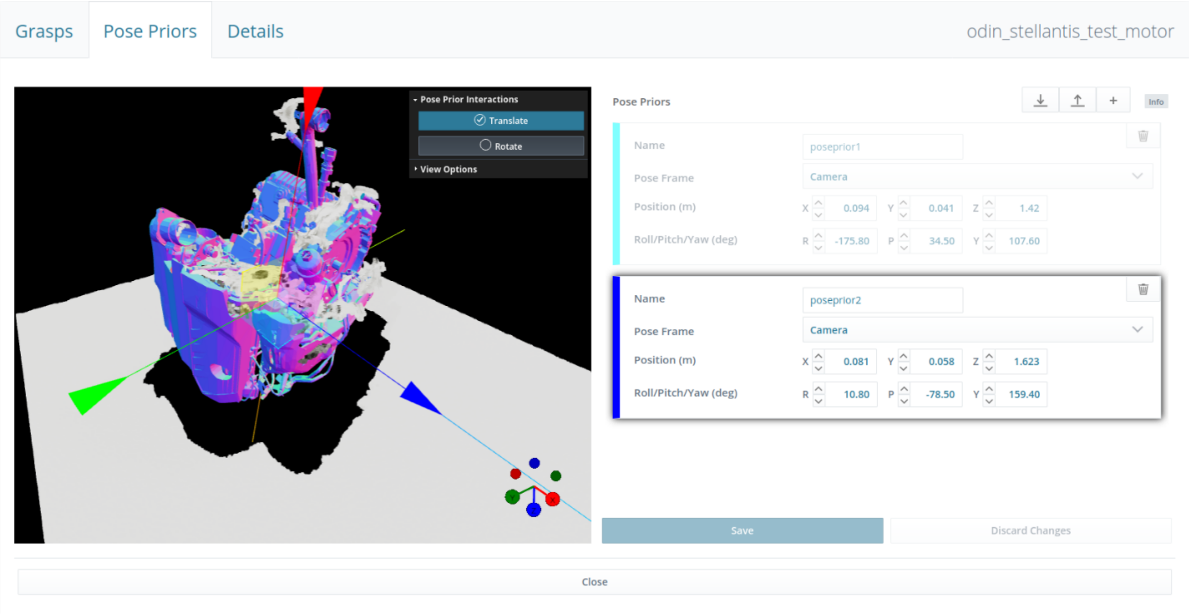


Figure 48: Configuration of pose priors for the Automotive motor in a simulation dataset

Sample detection results from simulation datasets with different materials and environment conditions are presented in Figure 49.

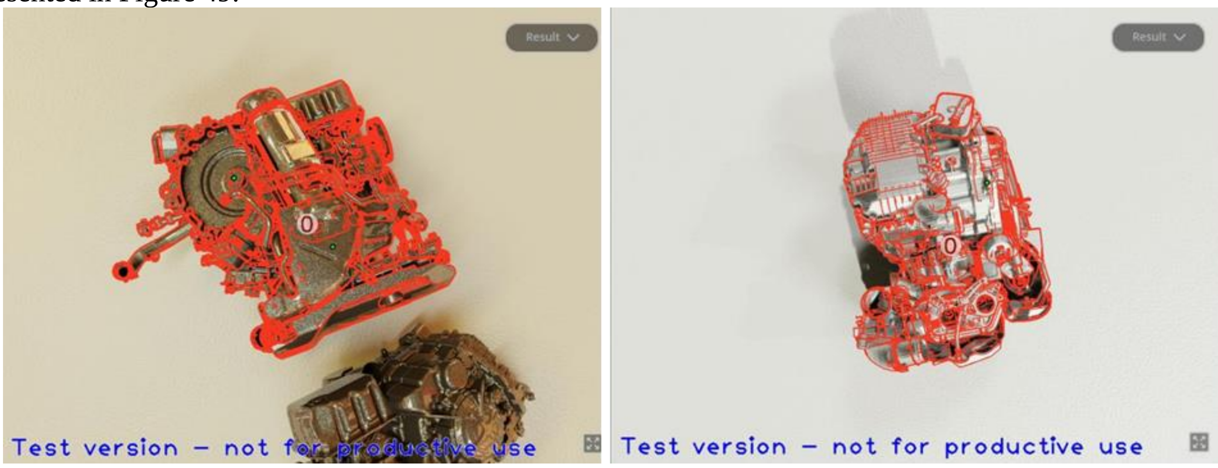


Figure 49: Sample detection results of the Automotive motor in the simulation environment

Quality check

The perception module for quality check will be deployed in Automotive business use-case AUTO-BUC-03 focusing on the quality inspection operation. This use case involves several types of inspection processes.

A selection inspection tasks have been identified for the initial evaluation of the Halcon-based solution. The results' from Halcon-based solution tests are presented in Figure 50.

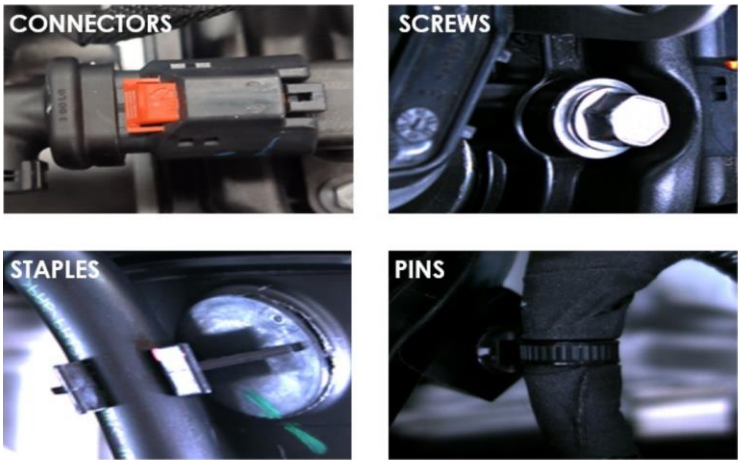
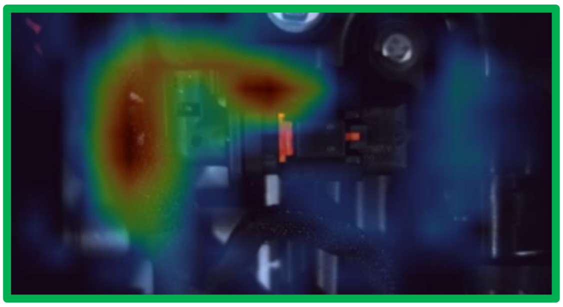
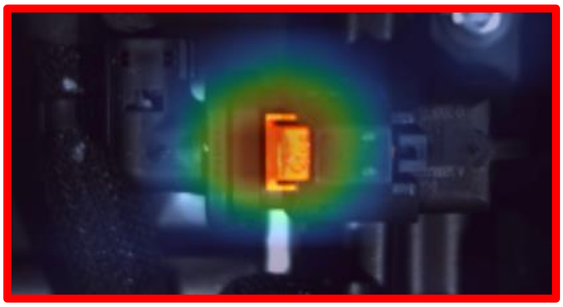


Figure 50: Sample parts on the Automotive engine used for the quality inspection evaluation

An initial test of the Halcon DL Toolkit software has been performed at ROBOCEPTION premises on a mock-up case consisting of checking whether the rc_visard power connector cable is correctly plugged in. In the meantime, the engine has been made available at partner facilities.

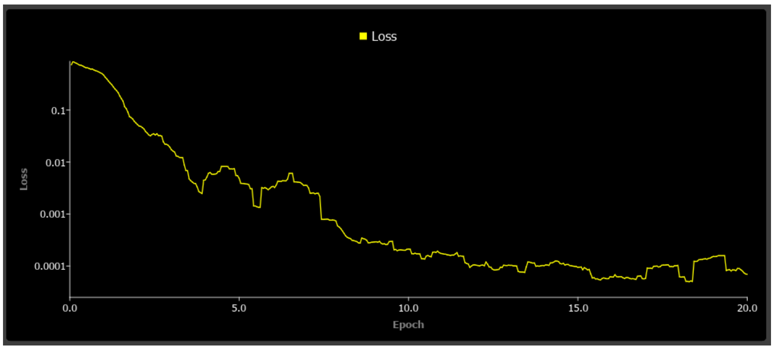
The results of the Halcon DL Toolkit on the recorded datasets captured at DGH premises are presented in the following table. In all cases, the system delivered good performance, with the error graphs converging to 0 during training.

Table 3:Quality inspection results using Halcon DL Toolkit

Connectors Dataset Details	
Number of OK images: 605 	Number of NOK images: 513 
HEATMAP OK EXAMPLE 	HEATMAP NOK EXAMPLE 

Connectors Training Results

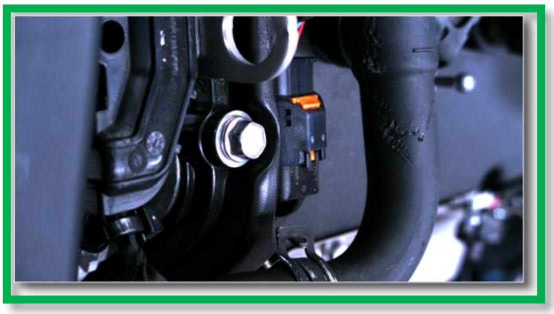
LOSS



TOP 1 ERROR

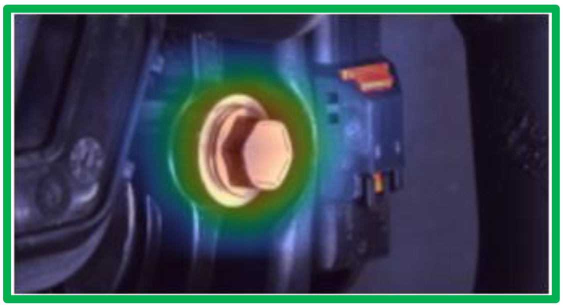
Screws Dataset Details

Number of OK images: 100

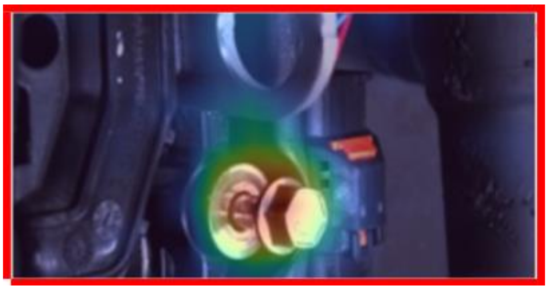


Number of NOK images: 118

HEATMAP OK EXAMPLE

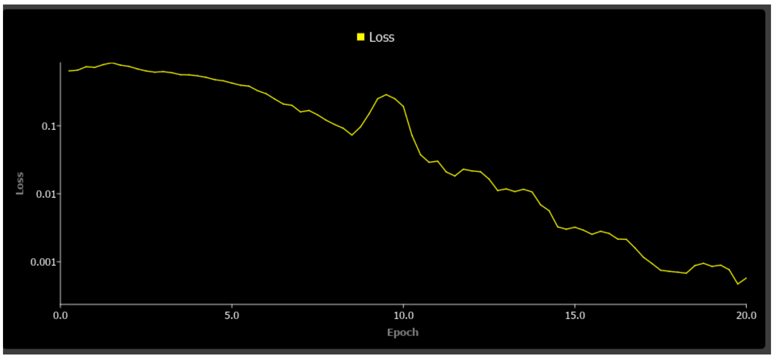


HEATMAP NOK EXAMPLE

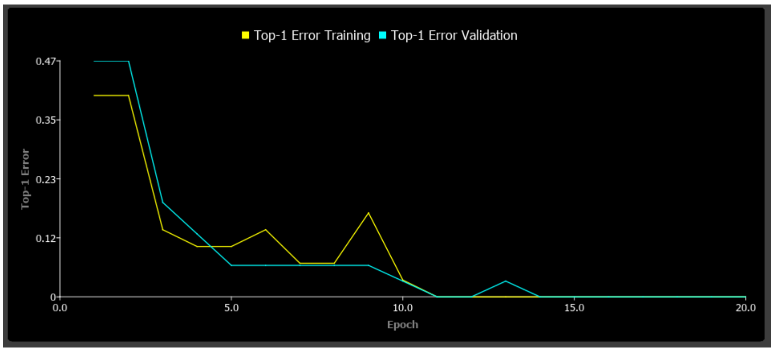


Screws Training Results

LOSS



TOP 1 ERROR



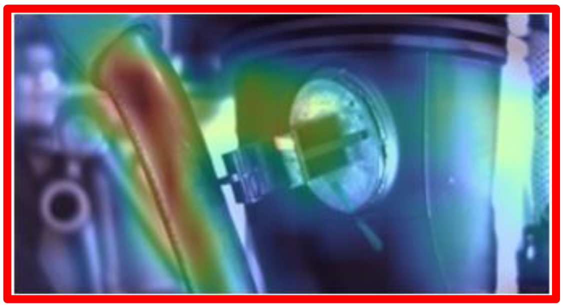
Staples Dataset Details

Number of OK images: 292

Number of NOK images: 202

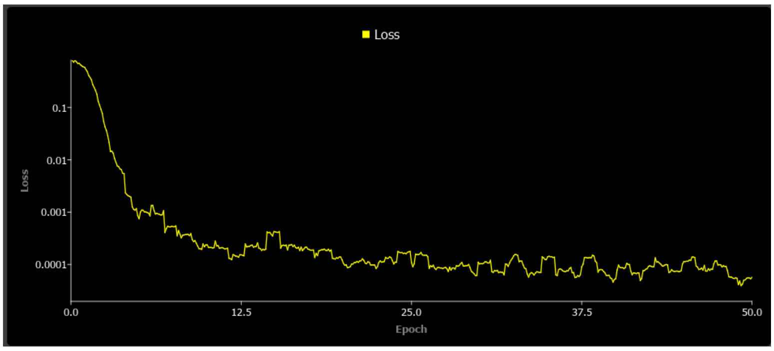
HEATMAP OK EXAMPLE

HEATMAP NOK EXAMPLE



Staples Training Results

LOSS



TOP 1 ERROR

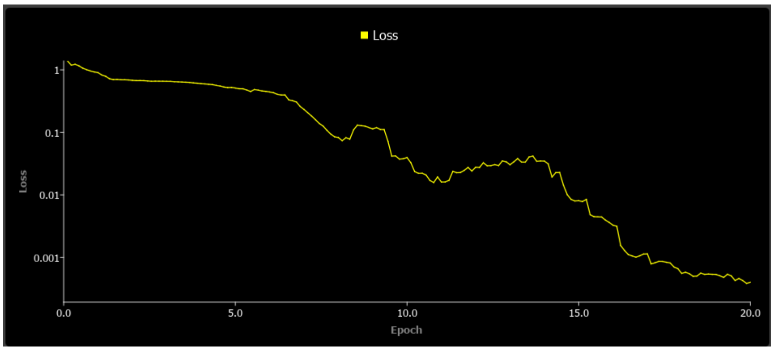
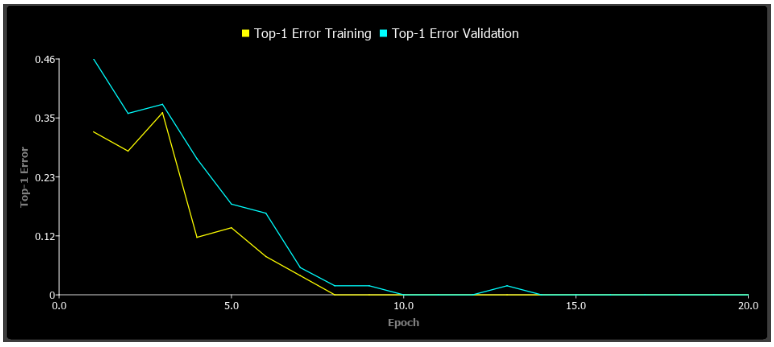
Pins Dataset Details

Number of OK images: 200

Number of NOK images: 179

HEATMAP OK EXAMPLE

HEATMAP NOK EXAMPLE

Pins Training Results	
LOSS	
TOP 1 ERROR	

<u>Perception for screwing while moving operations</u>

One of the features that enables the tool reconfiguration is robot's ability to adapt its tool's movements in real-time. This is crucial especially for the Automotive Pilot where parts (motor) are continuously moving. For this reason, a visual servoing module is being developed within WP2. This module will add the capability to carry out real-time control of the robot arms based on visual feedback received by the vision systems. This initial implementation includes the following features:

- Low-level robot control based on the direct servo and smart servo libraries provided by KUKA. The KUKA LBR iiwa arms are directly connected to ROS nodes which commands the manipulators in joint space with a frequency up to 400Hz.
- Cartesian twist controller developed by TECNALIA and implemented as ROS controllers (plugin). This controller accepts twist commands which can be referenced to any arbitrary tool and reference frame.
- Control framework to enable/disable low-level control of both KUKA LBR iiwa arms. This framework allows to mix high-level movements with control operations in any application.
- Simple visual servoing which generates cartesian twist commands based on the visual feedback. It implements a PI controller.

This initial prototype has been focused on the development and implementation of the basic framework for the visual servoing, which includes the Cartesian twist controller and the control framework. The initial prototype of visual servoing implementation on the reconfigurable tooling is presented in the following figure.

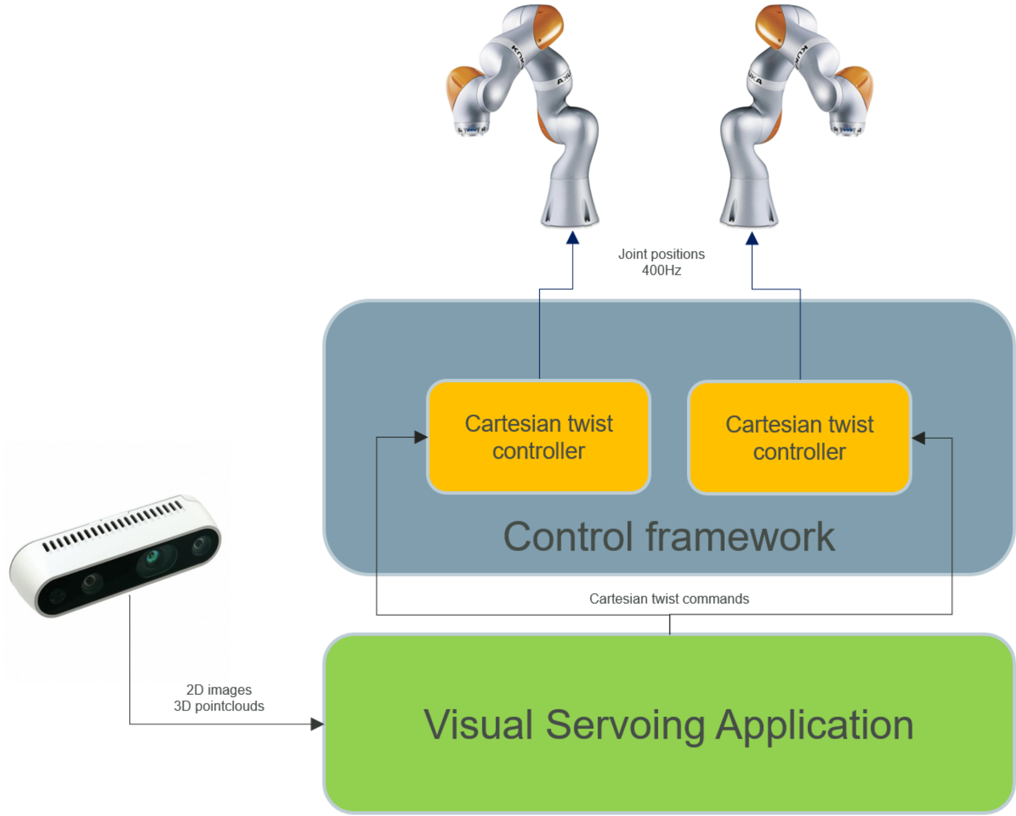


Figure 51: Visual Servoing schema for reconfigurable tooling

As for the perception module, its first implementation of the detection and pose estimation has been simplified using markers in order to test the complete control flow. However, during project's progression this module will be further developed in order to meet the Automotive pilot requirements.

5.5. Safety Related Parts of Control System (SRP/CS)

This section describes the updates since the preliminary SRP/CS architecture definition included into Section 3.3 of deliverable D1.3 in M9. The components and functions described herein are defined on the basis of the Design-based Risk Assessment and related Safety Concepts described in sections 7.1 and 7.5 of deliverable D5.1 (M18), respectively.

In order to implement the Safety Functions described in this section, several safety-rated devices need to be integrated into the pilot safety architecture. Figure 52 below, provides an overview of the architecture of the Safety Related Parts of Control System required for the implementation of the necessary Safety Functions addressed to reduce the risks identified in D5.1 to acceptable limits where reduction by intrinsically safe design measures is not applicable.

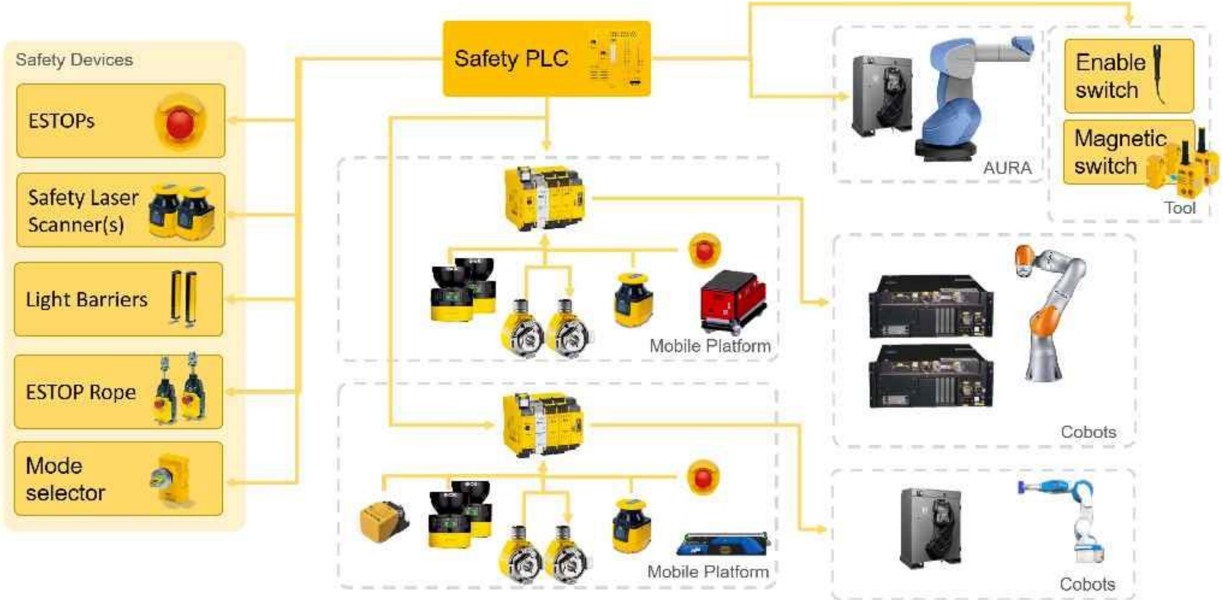


Figure 52: Safety Architecture for Automotive Pilot

The devices conforming the Automotive Pilot Safety Architecture are:

- Safety Controller. A fail-safe PLC or safety configurable relay is introduced in order to manage the safety logic at higher level.
- E-Stop switches and E-Stop rope, connected to the main safety PLC.
- Safety Laser Scanner, addressed to monitor the operator access to the AURA robot restricted space, and connected to the main safety controller
- Light Barriers, addressed to limit the access to the AURA robot restricted space from the motor and gearbox infeed storage area. They will be directly connected to the main safety controller.
- Mode selector to allow the switch between automatic operation and hand-guiding of AURA robot. It will be connected to the main safety controller.
- TECNALIA Mobile manipulator composed by the ROBOUT mobile platform and 2 KUKA IIWA collaborative manipulators. The platform is including its own Safe-Controller and internal architecture (see Section 2.1.3 of D1.3) that will interact with the cell main safety PLC.
- COMAU Mobile manipulator composed by a Racer 5 cobot [29] and an Agile mobile platform [30] which includes its own Safe-Controller and internal architecture (see Figure 6) that will interact with the cell main safety PLC.
- COMAU AURA collaborative robot which controller fail-safe signals to enable disable operation and emergency stop will be connected to the main safety controller.
- COMAU manual guidance device which includes the F/T sensor and 3-way enabling switch.

For this pilot, in order to reduce the risks identified in D5.1 to acceptable limits where reduction by intrinsically safe design measures is not applicable, the implementation of the following Safety functions is required:

a) The following Safety Functions are required for the motor and gearbox manipulation and assembly operation (AUTO-BUC-1):

- Static **Safety Laser Scanners** dynamic zones ensure the monitoring of the separation distance:
  - In case operator is detected in WARNING ZONE = Safety-Rated Reduced Speed must be activated.
  - In case operator enters in DANGER ZONE = Safety-Rated Monitored Stop (SOS) of AURA robot must be triggered.
- AURA robot **Safety-Rated monitored Speed**, according to EN ISO 10218-1 [31] 5.6.4, must monitor the correct speed of the robot when the human is out of the Warning Zone.
- AURA robot **Safety-Rated reduced Speed** must ensure a correct slow speed of the robot when the human is inside the Warning zone.
- AURA robot **Safety-Rated monitored Stop (SOS)** function, according to EN ISO 10218-1 [31] 5.5, must ensure a correct stop when the human enter in the Danger zone.
  - "**Deceleration Monitoring**" function is needed to ensure a correct STOP when the operator enters in the Danger Zone.
- **Space limiting Functions**: AURA robot cartesian safe limited position could be defined a volume in which the robot axes can move, considering the position and safety of the operation. A movement out of this area must generate a SOS.
  - Space limiting is used to enable the part (motor block or gearbox) release within a specific area above the conveyor. Out of this volume, the release of the part must be disabled.
- AURA robot **Safe Tool orientation** must be ensured the correct orientation of tool, to avoid a strange orientation which could position the motor or gearbox in a compromised position for stability or operator safety.
- As required by ISO/TS 15066 [34]**, mode selection** function is required in order to switch between robot AUTOMATIC mode and HAND-GUIDING. Any operating mode change should trigger a SOS in the robot and automatic operation restart needs to be prevented.
- AURA robot **Hand-Guiding function** must ensure that only actuations of the HG device (impedance and gravity compensation control) can generate Robot motion. Motion of pending movements, orders of other robot programs, and any other input are avoided.
- **3-way position switch** must be used to enable the Hand-Guided operation of AURA robot. The release of the enabling device and/or an excess of pressure on the device must generate a SOS in the Robot. This device should be installed on the End-effector.
  - This enabling function is complemented with a serialized **second switch (2-way or 3-way)** used to maintain the 2 operator hands in position, avoiding impact and trapping risks derived from the hand-guiding assisted manipulation.
- **Safety-rated detector** (magnetic switch or similar) are used to monitor the proper position and locking of the motor and gearbox grasping mechanism (see section 5.3). Motion of Robot must be disabled until the part is properly locked.
  - In case the function is disabled while the robot is moving, **a safe controlled stop** (**SS2**) is required and **warning acoustic or visual signals** needs to be triggered so that to inform the operator the part is not safely grasped.
- **Light barriers** on the infeed zone of motor blocks and gearboxes prevents operator access to the robot restricted zone trough this side of the cell. The actuation of these devices must generate a SOS.
- **ESTOP Push-Buttons** and **ESTOP Rope** stops all the actuators of the machine instantaneously and disables all the power supplies (electrical, pneumatic, etc…)
- Any fault or malfunction of the safety-rated functions must generate a Safety-Rated monitored Stop.

In general, the required performance level for the safety-related control system above described is PL "d" category "3" according to EN ISO 13849-1 [33]. This level is stipulated by standard type C EN ISO 10218-1 [31] (in section 5.4) for robots and robotic systems.

b) In relation to the kitting operation (AUTO-BUC-2) and the inspection operation (AUTO-BUC-3), the Safety Functions to be deployed are:

- Mobile platform should include a **Braking control system**. The minimum performance level (PLr) according to EN-ISO 13849-1 [33] required for these safety function will be PLd as stated into EN-ISO 3691-4 [35].
- Mobile platform onboard **Safety Laser Scanners** protective zones used to prevent collision of mobile platform towards the operator. A **protective stop** of the platform is triggered after the detection of a person in the path. The minimum performance level (PLr) according to EN-ISO 13849-1 required for these safety function will be PLd as stated into EN-ISO 3691-4.
    - As the mobile platform is following the conveyor, protective stop of the conveyor shall be triggered in order to avoid risk of trapping and/or part falling because of the difference of speed of mobile platform (stopped) and conveyor.
- The **adaption of these ESPE protective field** is based on several parameters and situations, such the **safe-monitored speed** of the mobile platform. For these safety functions PLd is required as stated into EN-ISO 3691-4 [35].
    - The size of the protective fields shall be so designed that trucks shall stop before contact between the rigid parts of the truck or load and a stationary person.
- **Automatic restart** is possible after obstacles or persons moved out of the detected range. It will follow appropriate warnings (optical and/or acoustic).
- **Muting of personnel detection means** will be implemented in order to allow the mobile platforms to work close the conveyor. The muted area of the protective zones will be the minimum necessary.
    - This muting needs to be triggered by a fail-safe signal, and only allowed in speeds bellow 0.3m/s, which should be guaranteed by the mobile platform safe-monitored speed function mentioned above. PLd is required as stated into EN-ISO 3691-4 [35].
- Mobile platform safety Laser Scanners (or an additional sensor safety scanner or safety radar) zones will ensure the **monitoring of the separation distance (SSM)** while the collaborative manipulators are in operation,
    - the configuration of protective zones shall be determined according to ISO/TS 15066 [34], and the change to of these field when the mobile platform is following the conveyor must be triggered by a fail-safe signal. The operation of the collaborative manipulators shall be enabled only when the platform is following the conveyor and protective fields are configured according this setup.
    - If operator enters in WARNING ZONE = Safety-Rated Reduced Speed must be activated on the manipulator/s, mobile platform and the conveyor shall adapt its speed if required.
    - If operator enters in DANGER ZONE = Safety-Rated Monitored Stop (SOS) of the collaborative robot must be triggered as well as the conveyor stop must be triggered.
- Collaborative robots **Safety-Rated Reduced Speed** and mobile platform **safe-monitored speed** must ensure a correct slow speed of the robot when the human is inside the Warning zone.
- Collaborative **safety-Rated monitored Stop** function and mobile platform **protective stop** must ensure a correct stop when the human enter in the Danger zone.
- Collaborative **Safety-Rated Soft Axis** must be defined to limit the restricted space to the front of the robot (conveyor side). A movement out of this area must generate a SOS.
- **Space limiting Functions**: Collaborative robot Cartesian Safe limited Position could be defined a volume in which the robot axes can move, considering the position and safety of the operation. A movement out of this area must generate a SOS.
    - Space limiting is used to enable mobile platform movements out of the "conveyor following configuration" only after both manipulators are completely (the whole body) located over the mobile platform footprint.
- Any fault or malfunction of the safety-rated functions must generate a Safety-Rated monitored Stop.
- **Emergency stop function** that complies with ISO 13850:2015 shall be provided in order to stop all truck movements and collaborative manipulators immediately. PLd is required as stated into EN-ISO 3691-4 [35] (mobile platform) and EN-ISO 10218-2 [32] (manipulator).

The above-described safety functions are the most representative for the business use cases explored in ODIN Automotive pilot. This list may be complemented with additional functions necessary for real production operation. Examples of additional safety functions to be further implemented could be the deactivation of charging connection before enabling mobile platform motion or collaborative robot teaching modes.

In addition, it must be considered that the safety functions described in this section, provides enough details to progress on the detailed design of pilot. Nonetheless, even the significant progress on the pilot conceptualization and design since the preliminary concepts stated into D1.3, the above-described functions have been identified in a preliminary design stage of pilots (based on simulations, CAD models, etc.) and in line with Design Risk Assessment presented in D5.1. After future onsite Risk Assessment on real pilots, additional risk reduction measures may be requested, thus affecting future design and/or Safety Related Parts of Control Systems (SRP/CS). More details on the safety concepts where these functions are applied as risk reduction measures, as well as the details of the required performance level according to ISO 13849-1 [33] can be found within deliverable D5.1.

6. AERONAUTICS PILOT

6.1. Overview

The Aeronautics pilot case is focused on the assembly process of the two parts for the Airbus A320Neo fan cowls. There are three operations involved (Figure 53):

1. drilling of holes on the two parts of the fan cowl, for the assembly components,
2. transport of the fan cowls between different workstations,
3. inspection of the parts.

For the successful execution of the drilling operation, one of the two LBR iiwa arms is equipped with an easily programmable drilling system. In order to program a drilling operation, an operator moves his arm to teach the robot where the drilling should be done. Once programmed, the robot arm can carry out drilling operations automatically. For the second operation, the LBR iiwa picks up safely a fan cowl on the transportation cart with its docking mechanism. The docking mechanism is equipped with human avoidance systems like magnetic grips for a safety docking between robot and cart or a safety strip that stops the robot when it detects a collision with another object in the layout. For the third operation, the second LBR iiwa arm is equipped with a visual inspection system. This system us used for different purposes such as detection of presence/ absence of components, checking the right assembly of components, detection of defects, etc.

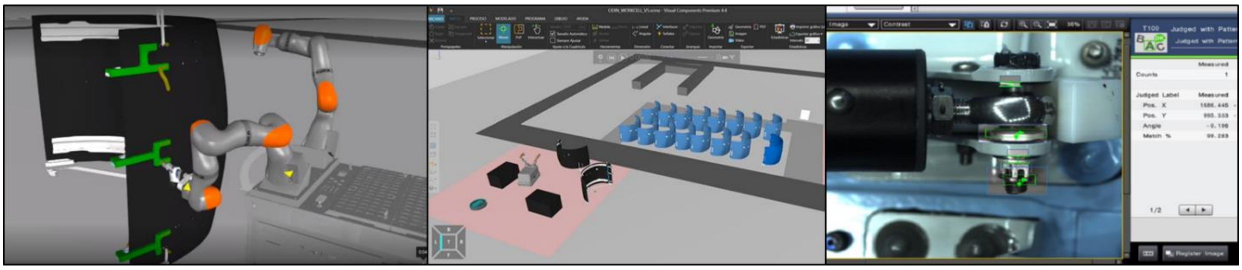


Figure 53: Aeronautics pilot overview

6.2. Autonomous mobile and robotic manipulators

This section presents the use of autonomous mobile and robotic manipulators in the Aeronautics pilot as described in Section 2.

As stated in the Aeronautics pilot specifications D1.1, the capacity to navigate in 3D is a key functionality of the system. This requirement comes mainly from the considerable size of the part to transport and how it greatly changes the shape of the volume that the robot occupies in the workspace. Beyond navigation itself (mapping, localization and planning) 3D obstacle perception and collision detection are the key elements to be assessed in the ODIN project.

For basic 3D navigation capabilities, an experimental suite developed by TECNALIA is being used. This suite is composed of several freely available open algorithms, put together to work in combination with the standard ROS navigation stack. This experimental suite has been tuned to be used in the ODIN robotic manipulator and is composed of the following modules:

- mapping,
- localization,
- planning.

Mapping module

The mapping process is performed using the LIO-SAM library [19]. This is a LiDAR-based odometry generation library that combines point-cloud matching with inertial measurement to accurately estimate sensor's movement. The point-cloud matching is performed against a 3D representation created from invariant points detected in the point-clouds. This 3D representation is dense enough to be used as a 3D map for later navigation.

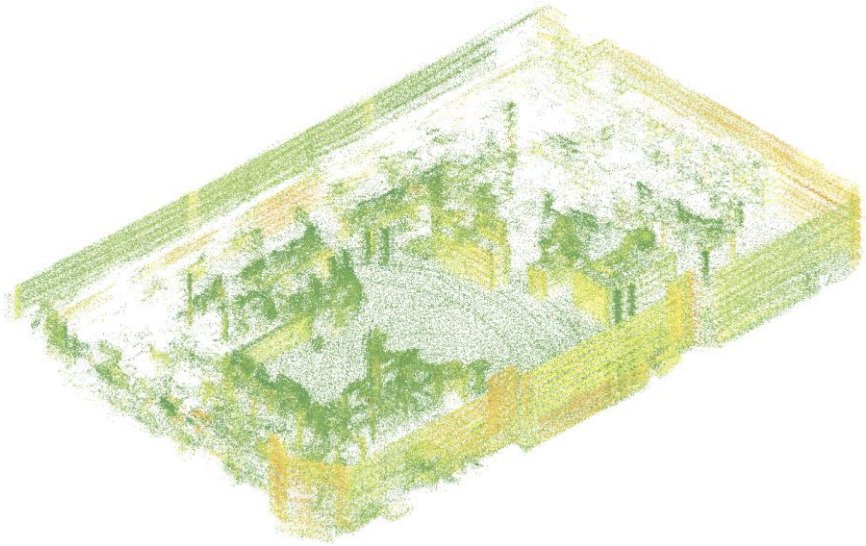


Figure 54: 3D map generated by LIO-SAM (ceiling cut out for visualization purposes)

Localization module

The HDL_localization library [20] is used for the localization module. This localization library performs Unscented Kalman Filter-based pose estimation. Pose update is estimated using inertial measurement and then is refined using a variant of the Normal Distribution Transform (NDT) point-cloud matching method against a global map.

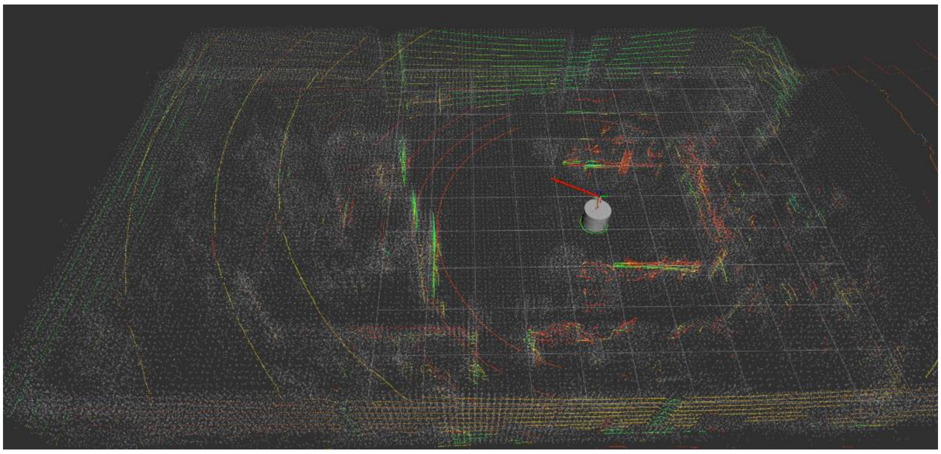


Figure 55: HDL_Localization using 3D LiDAR

Planning module

The planning part of the suite is actually composed by a combination of modules that generate a 2.5D or pseudo 3D representation of the environment from the 3D map. This 2.5D representation (also known as grid map or elevation map) is used to estimate the transitable space of the environment (i.e. the parts of the environment that the robot is able to reach by its own means).

The 2.5D representation is achieved using the grid_map module [21]. Grid_map is used to create an estimation of the floor's surface where each grid cell stores its elevation. Grid_maps are multilayered which allows to store other useful information computed from the 3D map or from the grid_map itself.

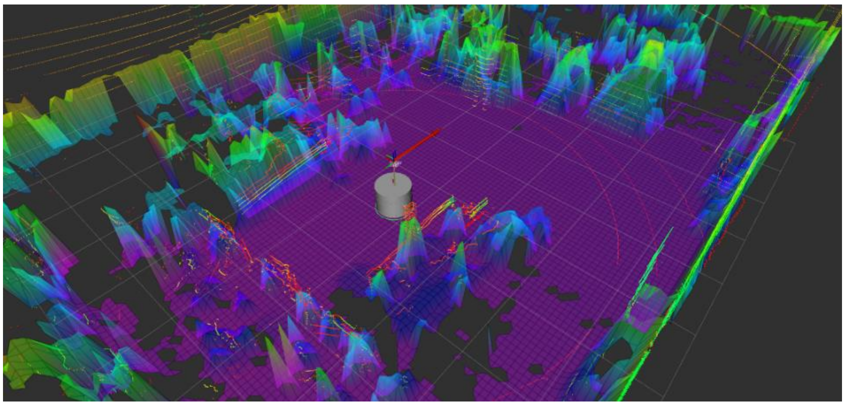


Figure 56: 2.5D elevation map (grid_map) obtained from the 3D map

From the information stored in the grid_map, the transitability space is calculated as a function of the slope and roughness of the terrain around each map cell. This transitability information is stored as a 2D costmap directly usable by the ROS standard navigation stack. Actual path planning and control are directly performed using ROS navigation modules (navfn and teb_local_planner).

Figure 57: 2D transitability map obtained from the elevation map

So far, this experimental 3D navigation suite lacks proper 3D obstacle representation and collision detection. Further efforts in the ODIN project will be focused in providing those capabilities to the experimental suite.

In order to provide safe transport operations, special transportations carts have been designed that minimize safety laser scanner occlusions and allows for a pulling point centred at the centre of mass of the set fan cowl plus cart. In addition to this cart, a reliable, safe and robust docking mechanism has been envisioned relaying on magnetic interlocks and anti-collision systems that allow disengaging the dragged carts whenever an excess force occurs.

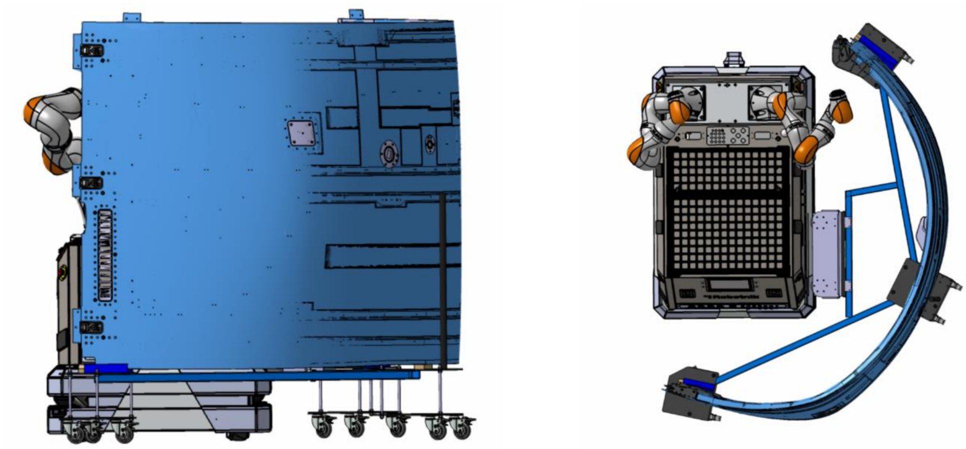


Figure 58: Transportation cart, fan-cowl and robot setup during transportation phase

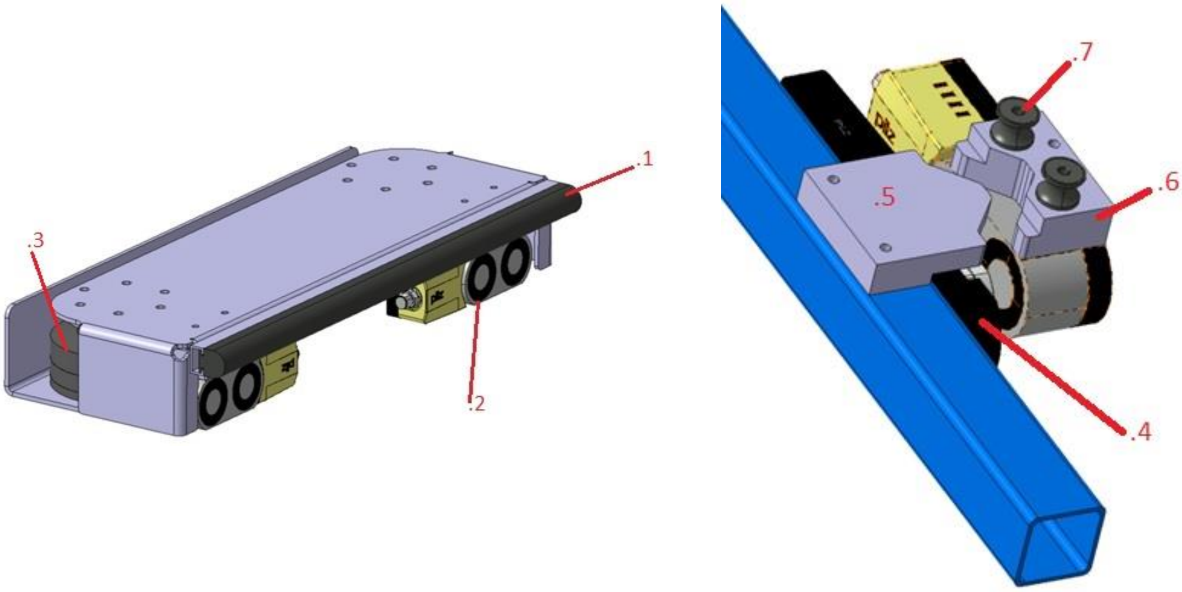


Figure 59: Transportation docking mechanism overview

This docking mechanism entails the following components:

Table 4: Docking mechanism components

Nº	Name	Description
1	Safety strip	Safety strip in the front area detects contact and stops the robot avoiding crushing problems.
2	Active Magnetic interlock PSENslock PILZ PSEN sl-1.0p 2.1	PSENslock PILZ provides greater safety, avoiding problems of entrapment and achieving a more reliable and optimal design. Magnetic holding force of 1000N is sufficient for the FC transport.
3	Anti-collision Zimmer CSR80	Pneumatic adjustable crash protection systems for protecting parts integrity in case of accidental collision.
4	Passive Magnetic interlock PSENslock PILZ PSEN sl-1.0p 2.1	Passive encoded interlock plate that allows safe detection of the contact.
5	Passive locating component	Ensure correct positioning and shear force loading for the docking mechanism.
6	Active locating component	
7	Shore A70 vibration dampeners	Vibration damper allows transport through floor areas that are not completely smooth, avoiding of the release of the interlocking mechanism.

6.3. Reconfigurable robot tooling

This section presents the tools planned to be used in the Aeronautics pilot for different operations execution.

Drilling machine for template/tooling based drilling

For the AERO-BUC-01 use case different drilling machine solutions will be investigated. In the first phase of the project pneumatic controlled machines will be used with the intention to test or integrate electric control machine. The first prototype is based on a Hi-shear Spacematic M1000 tool (Figure 60).

Figure 60: Hi-shear Spacematic M1000 drilling machine

This tool is semi-automatic device and has some disadvantages for an automated operation but it is equipped with the appropriate collet (drilling tip) for the drilling templates that are available. In parallel, a new collet has been ordered for the Setitec ST1200, which will allow better automated operation (Figure 61).

Figure 61: Setitec ST1200 drilling machine

<u>Fan cowl transportation tooling</u>

The AERO-BUC-02 use-case requires a custom transportation cart for safe and reliable fan cowl transportation. More details of the designed prototype will be presented in WP5 deliverables, but in the following picture (Figure 62) an overview of the prototype is presented.

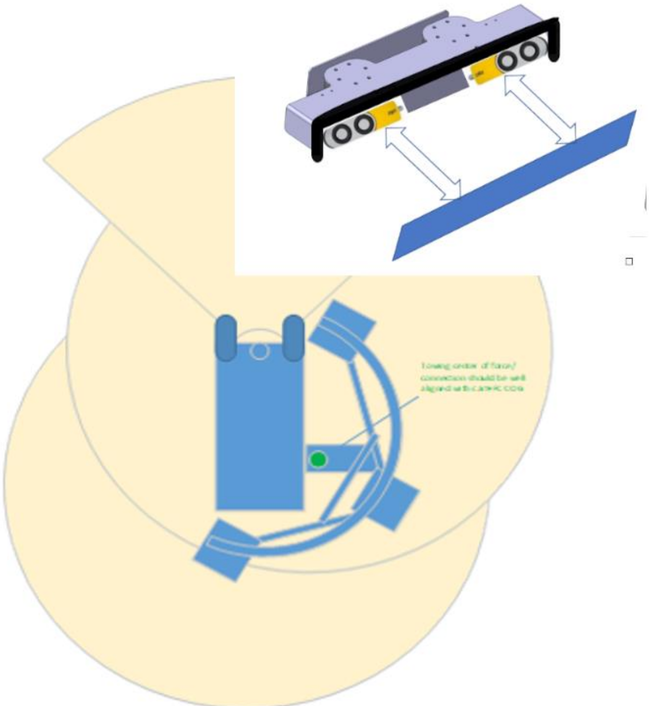


Figure 62: Fan cowl transportation cart

6.4. Process perception

This section presents the use of perception modules described in Section 4 in the Aeronautics pilot.

Object pose estimation using CAD models

The CADMatch 3D pose estimation module will be integrated in the Aeronautics business use-case AERO-BUC-01 (Template / Tooling based Drilling) for the detection of drilling templates on the fan cowls.

The drilling templates currently in use at AEROTECNIC facilities are not suitable for the automated drilling machine that will be mounted on the TECNALIA platform. The re-design of the drilling templates is currently in progress and a 3D printed mock-up is available for the initial testing.

The CAD file of the mock-up drilling template has been tested with the CADMatch software in the simulation environment, as shown in Figure 63.

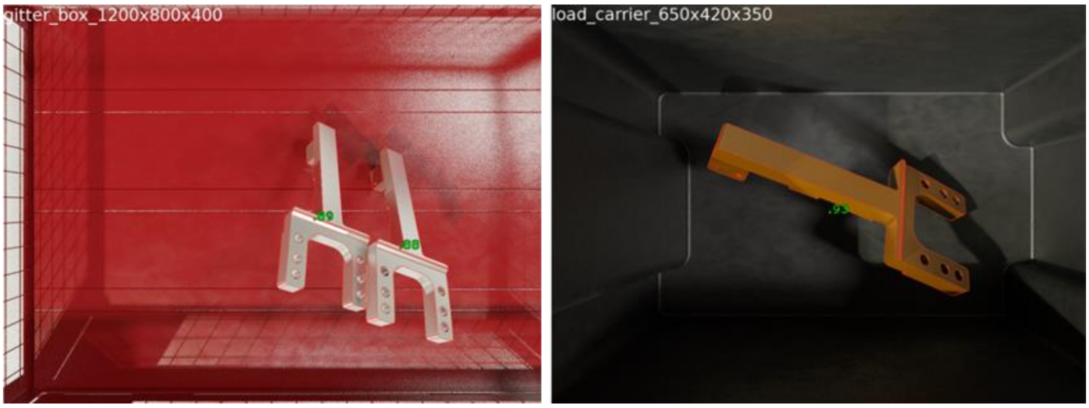


Figure 63: Sample detection results on simulation datasets. The green number represents the detection score computed by the detection software

Based on the object size, the indicative detection ranges are shown in Table 5 for different sensor models. The current plan is to use the robot-mounted rc_visard 65m and rc_visard 160m sensors.

Table 5: Indicative detection ranges for the drilling template mock-up for different sensor models

		rc_visard 65m/c	rc_visard 160m/c	rc_visard 160m-6	rc_viscore
Min Distance	Z [mm]	428	500	681	671
	Workspace [mm]	449x385	440x450	385x409	385x435
Max Distance	Z [mm]	671	671	1006	2916
	Workspace [mm]	740x604	645x604	645x604	2375x1891

Detection results in the simulation environment are shown in Table 6, where the median position and rotation accuracy achieved at different camera distances is shown. This simulation was realized with an rc_visard 160m. Ideally the camera should be as close as possible to the part to be detected.

Table 6: Simulation results of position and rotation accuracy (median values) at different camera distances

Camera distance [m]	dt [mm]	dR [deg]	Score
0.52 - 0.64	0.954	0.2	0.872
0.64 - 0.77	0.943	0.2	0.873
0.77 - 0.9	0.975	0.2	0.859
0.9 - 1.02	0.984	0.3	0.893
1.02 - 1.15	2.068	0.5	0.883

The object pose estimation has also been tested on the drilling template mock-up in real images, as shown in Figure 64.

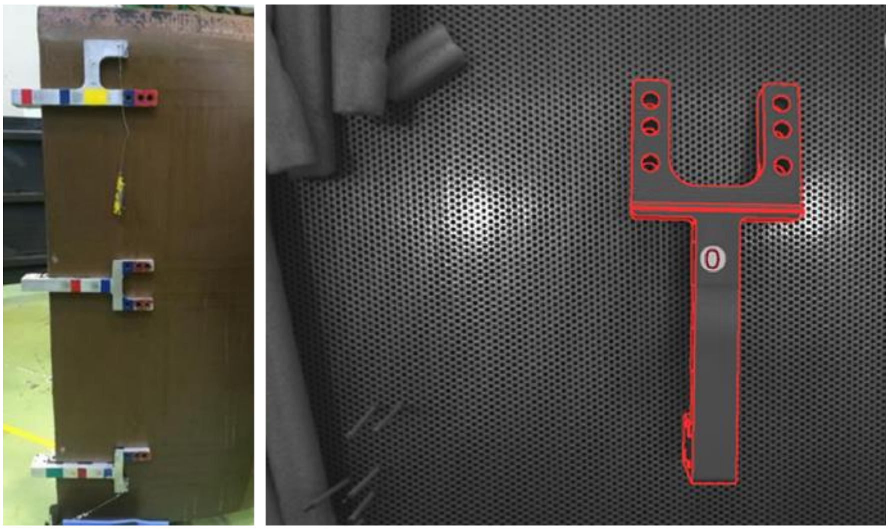


Figure 64: Picture of the drilling templates currently in use at AEROTECNIC (left) and detection result on the 3D printed mock-up of the drilling template

<u>Object inspection of Aeronautics mechanical assemblies</u>

The inspection procedure based on the creating of the 3D reference model and will be integrated in the AERO-BUC-03 pilot, according to the requirements and KPIs specified in the deliverable D1.1. The part to be inspected is the fan cowl element which is presented in Figure 65. There is a large number of different inspection operations that are currently being performed and that have been carefully analyzed.

Figure 65: Fan-Cowl LH (left) Fan-Cowl RH (right)

The inspection types of the fan cowl part can be classified in three different aspects according to the operational requirements:

- Inspection requiring manipulation, i.e. physically interacting with the parts to be inspected to check that they correctly perform the required movements,
- Conductivity tests,
- Visual inspection.

The perception solution to be integrated in the demonstrator will be focused on a subset of the visual inspection cases. In fact, the approach used fits within the following inspection cases:

- Presence/absence object inspection,
- Orientation checks,
- Correct mounting checks,
- Gaps and steps measurements (only for some specific cases).

Some examples of cases that fall under the described category are presented in Figure 66.

The Photoneo MotionCam-3D has been integrated in the robot platform (Figure 68). It is used for the creation of the model and the scanning operation of the fan cowl part. The camera has been integrated in the flange of the robot in an eye-in-hand configuration following the same setup used in the Fanuc experiments. Next steps will be focused on experiments of the Multiview fusion system developed using the real parts. In order to perform these experiments, partners' efforts are focused on the following topics:

- Improve the eye-in-hand calibration of the sensor based on the pointcloud.
- Generate the trajectories along the fan cowl surface to perform the scan.

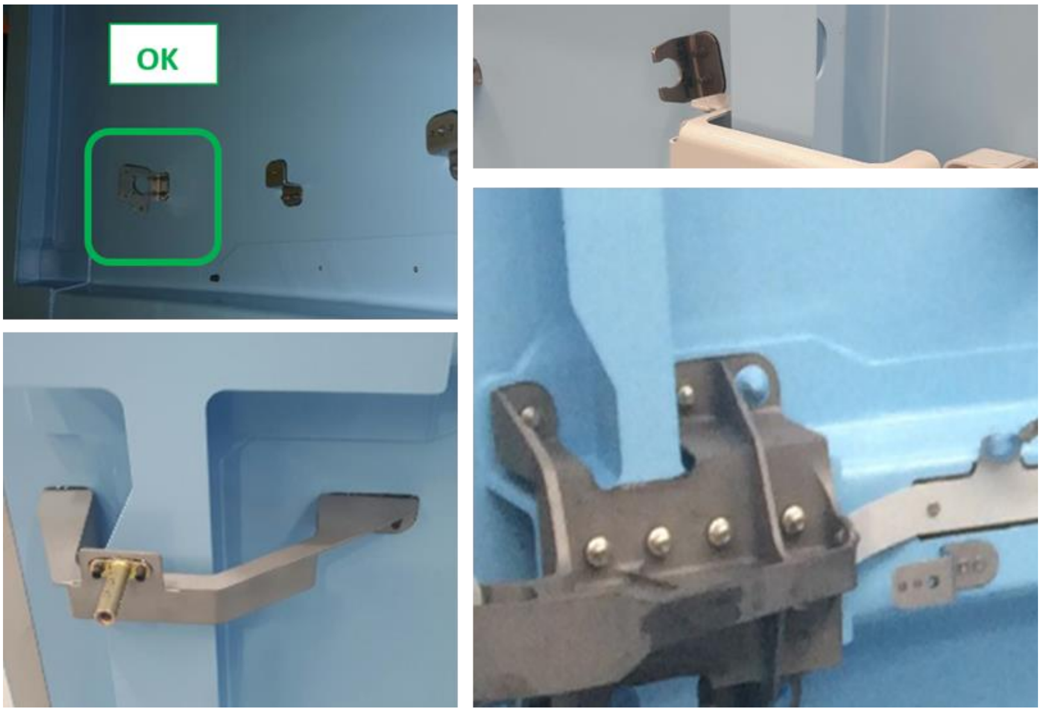


Figure 66: Examples of parts to be checked for presence and position

Figure 67: Robot positioned in the Fan-Cowl

Figure 68: 3D sensor eye-in-hand configuration

In a more advanced and versatile version, the main inspection tool design has been developed searching for high quality, highly repeatable results, adequate as an inspection process that in future will be certifiable under an aeronautics perspective. This inspection head achieves a particularly good versatility being able to cover a wide range of different inspections from presence of small details to detection of defects and inspection of relatively larger areas/components. This inspection tool will be supported and complemented by the additional systems described above. An overview of the included components would be the following:

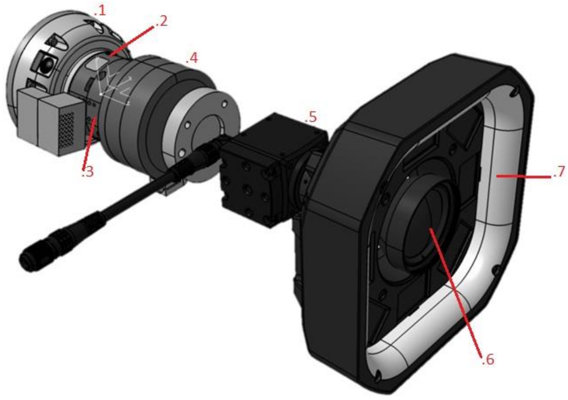


Figure 69: Inspection head overview

Table 7: Inspection head components

Nº	Name	Description
1	Robot flange KUKA LBR iiwa 7 R800	Collaborative robot arm with 7kg of load capability.
2	Fixed tool changer: Zimmer WWR50F	Fixed and mobile automatic tool changing systems, including WER2000FSI32-05-B and WER2000LSI32-05-B connectors for quick interchange of the connections between all the following components.
3	Mobile tool changer: Zimmer WWR50B	
4	Anti-collision:Zimmer CSR50	Pneumatic adjustable crash protection system for protecting parts integrity in case of accidental collision.
5	Camera:Keyence CA-H2100C	High resolution camera providing capability of inspecting large areas in one shot
6	Lens: Edmund Optics LT	Fixed focal distance, automatic focus liquid lens in order to provide focus at different distances/fields of view
7	Pattern projection lighting: Keyence CA-DQP12X	Multi-purpose lighting system, providing the required versatility for 2D and 3D inspections

6.5. Safety Related Parts of Control System (SRP/CS)

The content of this section is describing the updates since the preliminary SRP/CS architecture definition included into Section 3.3 of deliverable D1.3 in M9. The components and functions described herein are defined on the basis of the Design-based Risk Assessment and related Safety Concepts described in sections 8.1 and 8.5 of deliverable D5.1 (M18), respectively.

In order to implement the Safety Functions described in this section, several safety-rated devices need to be integrated into the pilot safety architecture. Figure 70 below, provides an overview of the architecture of the Safety Related Parts of Control System required for the implementation of the necessary Safety Functions addressed to reduce the risks identified in D5.1 to acceptable limits where reduction by intrinsically safe design measures is not applicable.

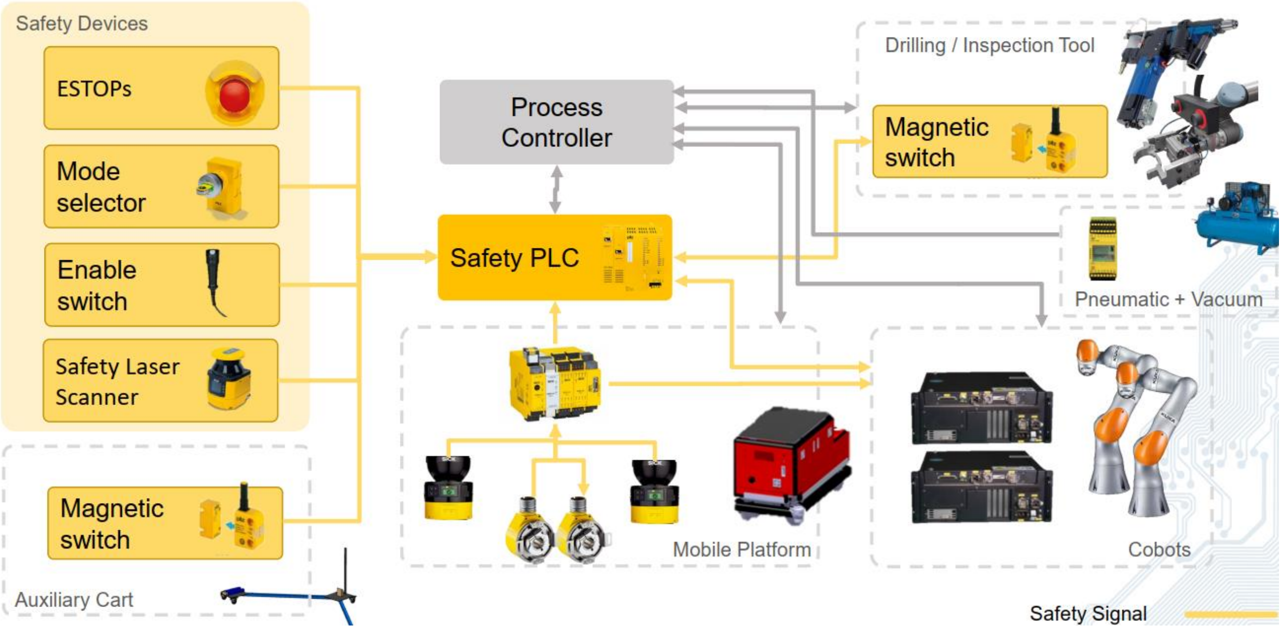


Figure 70: Safety Architecture for Aeronautics Pilot

The devices conforming the Aeronautics Pilot Safety Architecture are:

- Safety Controller. A fail-safe PLC or safety configurable relay mounted on the mobile platform is introduced in order to manage the safety logic at higher level.
- E-Stop switches connected to the main safety PLC to perform the emergency stop function of the robot, in addition to the mobile manipulator already available ES switches.
- Safety Laser Scanner (or safety radars), addressed to monitor the operator access to the collaborative robots restricted space, and connected to the main safety controller.
- Mode selector to allow the switch between automatic operation and manual (teaching) operation. It will be connected to the main safety controller.
- Enabling switch connected to the main safety controller addressed to enable manipulators operation in manual (teaching) mode.
- Magnetic safety locking system addressed to detect and attach the presence of the auxiliary cart.
- Miniature fail-safe magnetic switch to monitor the proper attachment of the drilling tool.
- Fail-safe inductive sensors to detect the mobile robot position towards the fawn-cowls.
- Fail-safe photocell or laser sensors to detect the proper location of the fan-cowl, as it will act as a mechanical guard.
- Safety border installed along the auxiliary cart coupling mechanism, protecting collision with or trapping of operator.
- TECNALIA Mobile manipulator composed by the ROBOUT mobile platform and 2 KUKA iiwa collaborative manipulators. The platform is including its own Safe-Controller and internal architecture (see Section 2.1.3 of D1.3) that will interact with the cell main safety PLC.

For this pilot, in order to reduce the risks identified in D5.1 to acceptable limits where reduction by intrinsically safe design measures is not applicable, the implementation of the following Safety functions is required:

a) The following Safety Functions are required for the drilling (AERO-BUC-1) and inspection (AERO-BUC-3) operations:

- Mobile platform should include a **Braking control system**. The minimum performance level (PLr) according to EN-ISO 13849-1 [33] required for these safety function will be PLd as stated into EN-ISO 3691-4 [35].
- Mobile platform onboard **Safety Laser Scanners** protective zones used to prevent collision of mobile platform towards the operator. A **protective stop** of the platform is triggered after the detection of a person in the path. The minimum performance level (PLr) according to EN-ISO 13849-1 required for these safety function will be PLd as stated into EN-ISO 3691-4 [35].
    - As the mobile platform is following the conveyor, protective stop of the conveyor shall be triggered in order to avoid risk of trapping and/or part falling because of the difference of speed of mobile platform (stopped) and conveyor.
- The **adaption of these ESPE protective fields** is based on several parameters and situations, such the **safe-monitored speed** of the mobile platform. For these safety functions PLd is required as stated into EN-ISO 3691-4 [35].
    - The size of the protective fields shall be so designed that trucks shall stop before contact between the rigid parts of the truck or load and a stationary person.
- **Automatic restart** is possible after obstacles or persons moved out of the detected range. It will follow appropriate warnings (optical and/or acoustic).
- **Muting of personnel detection means** will be implemented in order to allow the mobile platforms to work close to the fan-cowl and during the coupling to the auxiliary cart. The muted area of the protective zones will be the minimum necessary.
    - This muting needs to be triggered by a fail-safe signal, and only allowed in speeds bellow 0.3m/s, which should be guaranteed by the mobile platform safe-monitored speed function mentioned above. PLd is required as stated into EN-ISO 3691-4 [35].
- Mobile platform safety Laser Scanners (or an additional sensor safety scanner or safety radar) zones will ensure the **monitoring of the separation distance (SSM)** while the collaborative manipulators are in operation,
    - the configuration of protective zones shall be determined according to ISO/TS 15066 [34], and the change to of these field when the mobile platform is following the conveyor must be triggered by a fail-safe signal. The operation of the collaborative manipulators shall be enabled only when the platform is following the conveyor and protective fields are configured according this setup.
    - If operator enters in WARNING ZONE = Safety-Rated Reduced Speed must be activated on the manipulator/s, mobile platform and the conveyor shall adapt its speed if required.
    - If operator enters in DANGER ZONE = Safety-Rated Monitored Stop (SOS) of the collaborative robot must be triggered as well as the conveyor stop must be triggered.
- Collaborative robots **Safety-Rated Reduced Speed** and mobile platform **safe-monitored speed** must ensure a correct slow speed of the robot when the human is inside the Warning zone.
- Collaborative **safety-Rated monitored Stop** function and mobile platform **protective stop** must ensure a correct stop when the human enter in the Danger zone.
- Collaborative **Safety-Rated Soft Axis** must be defined to limit the restricted space to the front of the robot (towards fan-cowl side). A movement out of this area must generate a SOS.
- **Monitoring of determined positions** of the mobile manipulator respective to the fan-cowl and **Monitoring of fan-cowl presence** shall be implemented. This function will then be used to:
    - enable the collaborative robot operation. The loss of this position while collaborative robots are in operation shall trigger SOS function of manipulators and mobile platform.
    - trigger the additional safety laser scanner (or safety radars) configuration according to this operation.

- **Space limiting Functions**: Collaborative robots Cartesian Safe limited Position could be defined a volume in which the robot axes can move, considering the position and safety of the operation. A movement out of this area must generate a SOS.
    - Space limiting is used to enable mobile platform movements out of the "conveyor following configuration" only after both manipulators are completely (the whole body) located over the mobile platform footprint.
- Any fault or malfunction of the safety-rated functions must generate a Safety-Rated monitored Stop.

  Emergency stop function that complies with ISO 13850:2015 shall be provided in order to stop all truck movements and collaborative manipulators immediately. PLd is required as stated into EN-ISO 3691-4 [35] (mobile platform) and EN-ISO 10218-2 (manipulators).

b) In relation to the transport operation (AERO-BUC-2) the following Safety Functions are required:

- Mobile platform should include a **Braking control system**. The minimum performance level (PLr) according to EN-ISO 13849-1 [33] required for these safety function will be PLd as stated into EN-ISO 3691-4 [35].
- Mobile platform onboard **Safety Laser Scanners** protective zones used to prevent collision of mobile platform towards the operator. A **protective stop** of the platform is triggered after the detection of a person in the path. The minimum performance level (PLr) according to EN-ISO 13849-1 required for these safety function will be PLd as stated into EN-ISO 3691-4 [35].
    - As the mobile platform is following the conveyor, protective stop of the conveyor shall be triggered in order to avoid risk of trapping and/or part falling because of the difference of speed of mobile platform (stopped) and conveyor.
- The **adaption of these ESPE protective fields** is based on several parameters and situations, such the **safe-monitored speed** of the mobile platform. For these safety functions PLd is required as stated into EN-ISO 3691-4 [35].
    - The size of the protective fields shall be so designed that trucks shall stop before contact between the rigid parts of the truck or load and a stationary person.
- **Automatic restart** is possible after obstacles or persons moved out of the detected range. It will follow appropriate warnings (optical and/or acoustic).
- **Muting of personnel detection means** will be implemented in order to allow the mobile platforms to work close to the fan-cowl and during the coupling to the auxiliary cart. The muted area of the protective zones will be the minimum necessary.
    - This muting needs to be triggered by a fail-safe signal, and only allowed in speeds bellow 0.3m/s, which should be guaranteed by the mobile platform safe-monitored speed function mentioned above. PLd is required according to EN-ISO 3691-4 [35].
    - During the **coupling** between mobile platform with the auxiliary cart, the **monitoring** of collision or trapping operator by means of the **safety border** between auxiliary cart coupling devices and other structures. A protective stop of the platform should be triggered if contact is detected on this device.
- **Monitoring of auxiliary cart presence and proper coupling** shall be implemented. This function will then be used to:
    - triggering the additional safety laser scanner (or safety radars) configuration according to this operation and the new platform payload. PLd is required for this function according to EN-ISO 3691-4 [35].
- **Space limiting Functions**: Collaborative robots Cartesian Safe limited Position could be defined a volume in which the robot axes can move, considering the position and safety of the operation. A movement out of this area must generate a SOS.
    - Space limiting is used to enable mobile platform movements out of the "conveyor following configuration" only after both manipulators are completely (the whole body) located over the mobile platform footprint.
- Any fault or malfunction of the safety-rated functions must generate a Safety-Rated monitored Stop.

- **Emergency stop function** that complies with ISO 13850:2015 shall be provided in order to stop all truck movements and collaborative manipulators immediately. PLd is required as stated into EN-ISO 3691-4 [35] (mobile platform) and EN-ISO 10218-2 (manipulators).

As well as indicated in section 5.5, the above-described safety functions are the most representative for the business use cases explored in ODIN. This list may be complemented with additional functions necessary for real production operation.

Even the significant progress on the pilot conceptualization and design since the preliminary concepts stated into D1.3, the above-described functions have been identified in a preliminary design stage of pilots (based on simulations, CAD models, etc.) and in line with Design Risk Assessment presented in D5.1. After future onsite Risk Assessment on real pilots, additional risk reduction measures may be requested, thus affecting future design and/or Safety Related Parts of Control Systems (SRP/CS). More details on the safety concepts where these functions are applied as risk reduction measures, as well as the details of the required performance level according to ISO 13849-1 [33] can be found within deliverable D5.1.

7. WHITE GOODS PILOT

7.1. Overview

The White Goods pilot is derived from a collaborative application installed in the Microwave Factory of Biandronno Plant (Italy). Based on the reconfiguration scenarios of D1.1, ODIN solution for white goods will showcase the capability of handling different product variations under the same workstation (Figure 71). Thus, the white goods pilot will focus on the assembly of an electrical oven and a gas cooktop. These assembly operations include the installation of different parts such as transformers, cooktops and knobs, on the main body of the respective white goods product. A human operator performs these assembly operations, while a UR10 collaborative robot is feeding the human operator with the parts. A cardboard and a separator part are also included in the pilot, and the cobot is also responsible for safely removing them from the table surface using a custom reconfigurable vacuum gripper.

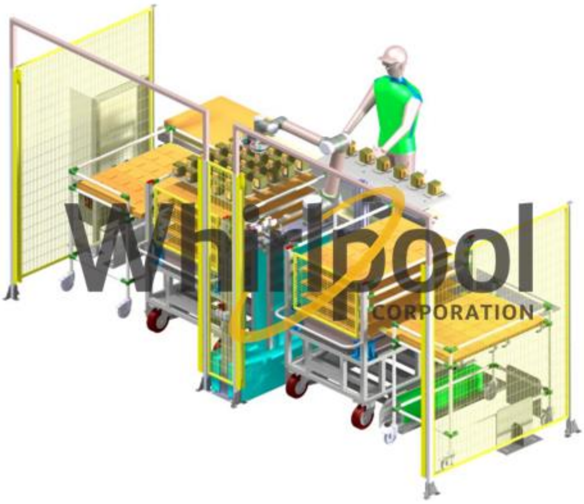


Figure 71. White goods pilot overview

7.2. Reconfigurable robot tooling

Three different types of grippers have been selected for the successful execution of parts manipulation in the White Goods pilot of ODIN. A magnetic gripper has been selected for the transportation of cooktops and transformers by the robot. Additionally, a flexible pneumatic gripper is selected for knobs' manipulation while a vacuum gripper has been introduced for cardboards and separators removal.

<u>Magnetic Gripper</u>

A magnetic gripper has been selected for the transportation of cooktops and transformers by the robot in the White Goods pilot of ODIN (Figure 72).

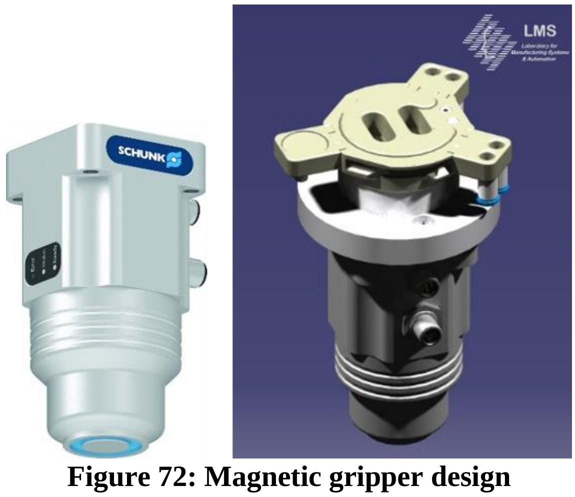


Figure 72: Magnetic gripper design

A SCHUNK EMH-36B [22] electromagnetic gripper has been selected for this task with the following specifications:

Table 8: Magnetic gripper specifications

Schunk EMH – 36B magnetic gripper	Specification
Operation principle	Permanent Magnet
Power Supply	24Vdc
Holding Force	850N
Weight	1kg
Combined weight of plastic safety cover and toolchanger	0.6kg
Total weight	1.6kg
Total height	190mm

A custom flange has been designed to connect the selected gripper with this pilot's cobot (Figure 73).

Figure 73: Flange for magnetic gripper

This gripper is enabled and disabled through Boolean control signals. The safety of grasping process is ensured thanks to the permanent magnet of this gripper. In case of a power failure, the permanent magnet is designed to retain its magnetic force.

Additionally, a safety plastic cover without sharp edges has been designed to wrap around the magnetic gripper increasing the safety in the HRC environment (Figure 74).

Figure 74: Safety cover for magnetic gripper

The selected magnetic gripper is able to manipulate parts that have a surface that is made of a ferromagnetic material and with weight up to 8.5 kg. The gripper's properties ensure versatility regarding the manipulated parts in terms of weight, geometry and material. However, the manipulated part's magnetic surface size, unevenness and material must be considered.

Flexible Gripper

A FESTO DHEF – 20 flexible [23] gripper is selected for the manipulation of the knob. This gripper is able to manipulate parts with different geometrical shapes. It consists of a double-acting cylinder, with one chamber filled with compressed air and the second one permanently filled with water. The water-filled silicone cap, is fitted with elastic silicone moulding and it is designed to wrap itself around the items being gripped in a flexible and form-fitting manner. The flexible gripper consists of a pneumatic drive and the inverting cap, which is connected to the piston rod at its tip. The cylinder motion pulls the cap tip inwards, allowing objects to be gripped during the inverting motion. This gripper is presented in Figure 75 following up with its specifications.

Figure 75: Flexible gripper

Table 9: Flexible gripper specifications

Festo flexible gripper	Specification
Operation principle	Pneumatic inverting cap
Pressurized Air Supply	1-8bar
Effective load	Up to 1kg
Weight	0.5
Combined weight of plastic safety cover and toolchanger	0.5kg
Total weight	1 kg
Total height	250 mm

Similarly to the magnet gripper, a custom flange has been designed to connect the selected flexible gripper with this pilot's cobot as presented in Figure 76.

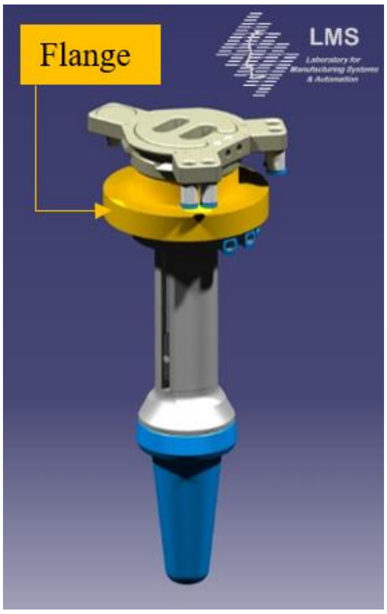


Figure 76: Flange for flexible gripper

Two sensors can be mounted in the T-slots on the side of the gripper to report the piston position and provide feedback about the gripping process. Both the holding and the release mechanisms are triggered pneumatically. No additional energy is necessary for the holding process. The force and the deformation of the silicone part can be set very precisely with the aid of a proportional valve.

The selected gripper's inverting cup part is flexible and yielding. Furthermore, a safety cover will be installed to make the overall gripper's surface smoother as presented in Figure 77. In the final design of this safety cover model, all sharp edges were removed increasing the safety during human – robot collaboration.

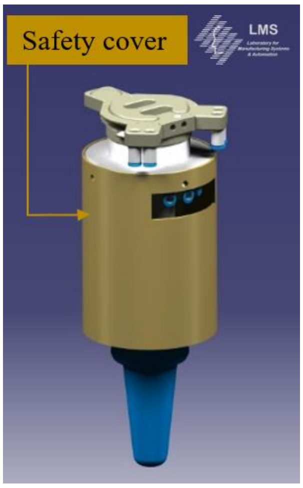


Figure 77: Safety cover for flexible gripper

Using the selected gripper, different parts with very substantial differences in geometric details are able to be manipulated. The part's geometric details to be grasped are referred as part's diameter to be gripped. Manipulated parts' diameter should be within the range of 12mm to 38mm. In parallel, the weight of the manipulated parts should be check.

<u>Vacuum gripper</u>

This gripper is used for the removal of the cart boards and separators from transformers cart. This gripper consists of 10 SCHMALZ suction cups (Figure 78) [24] with the following characteristics:

- Weight: 7.9 gr
- Shore hardness: 65
- Suction force @600 mbar: 20.7N
- Pull-off force: 30.6N
- Curve radius (min): 35 mm
- Number of folds: 1.5
- Cable external diameter: 6mm

The vacuum gripper which is used in this pilot is presented in Figure 78.

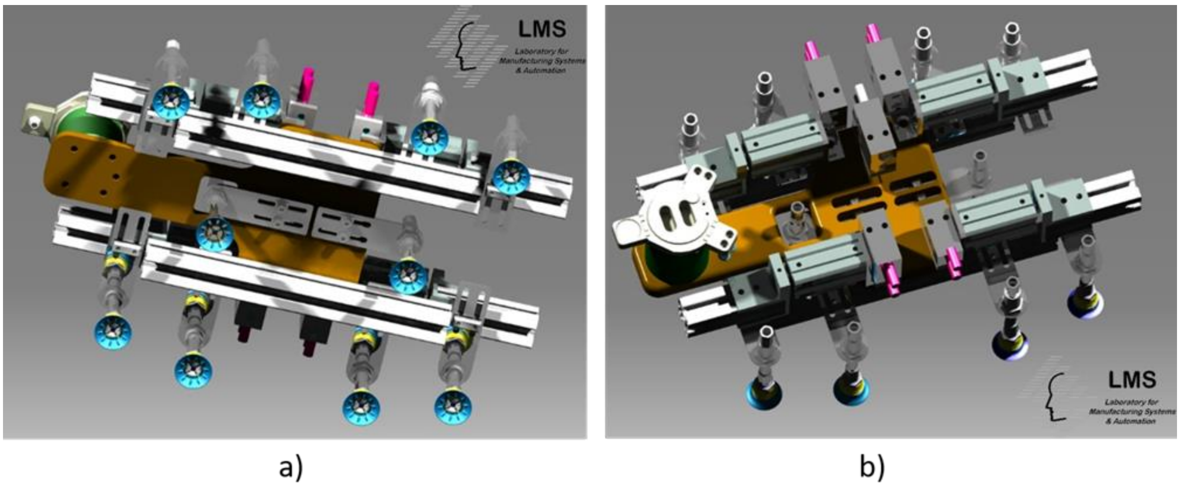


Figure 78: Vacuum gripper

The vacuum gripper utilizes the vacuum pumps and cups for grasping the parts. These components are installed on the main body of the vacuum gripper which is presented in Figure 79.

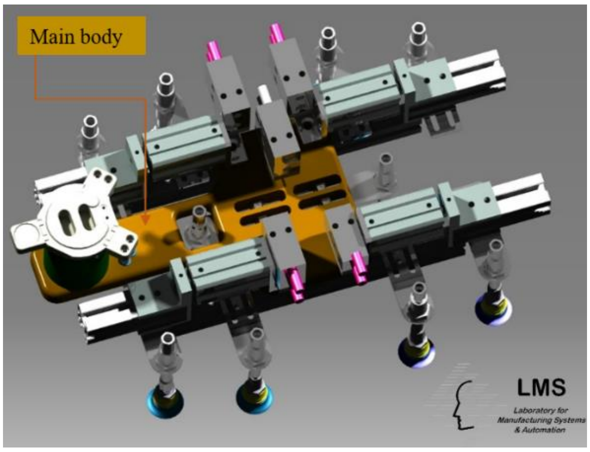


Figure 79: Vacuum gripper's main body

This gripper consists of a metallic frame with a telescopic adjustable mechanism to automatically change the dimensions of the area to be used for the grasping action (Figure 80). The vacuum gripper is designed to be able to grasp the cardboard and separator parts that have small weight and a flat surface. It is designed with integrated linear actuators that are able to increase the distance of the pumps (Figure 81). Due to its adjustable length, it can ensure better grasping of parts with a possibly bigger surface.

Table 10: Vacuum gripper specifications

Vacuum gripper	Specification
Operation principle	Pneumatic suction cups
Total weight	5 kg
Total height	200 mm
Telescopic actuator stroke	50mm

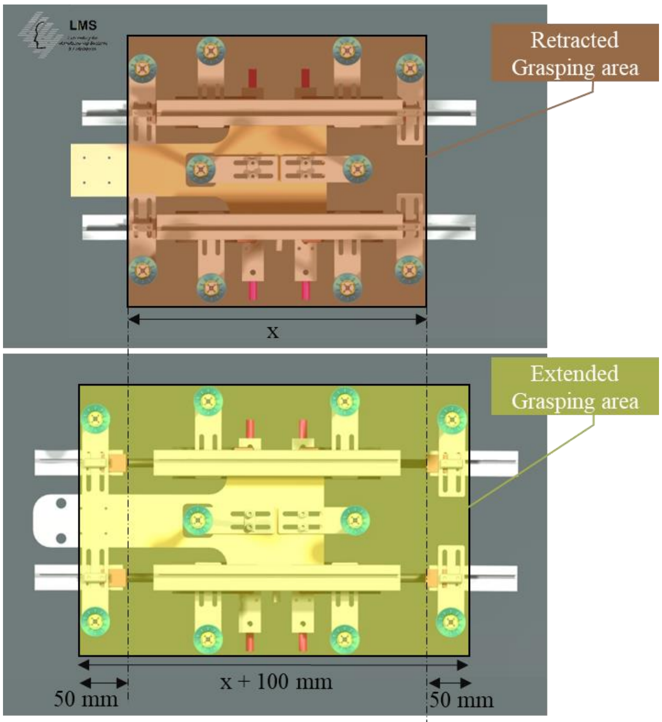


Figure 80: Vacuum gripper retracted and extended grasping area

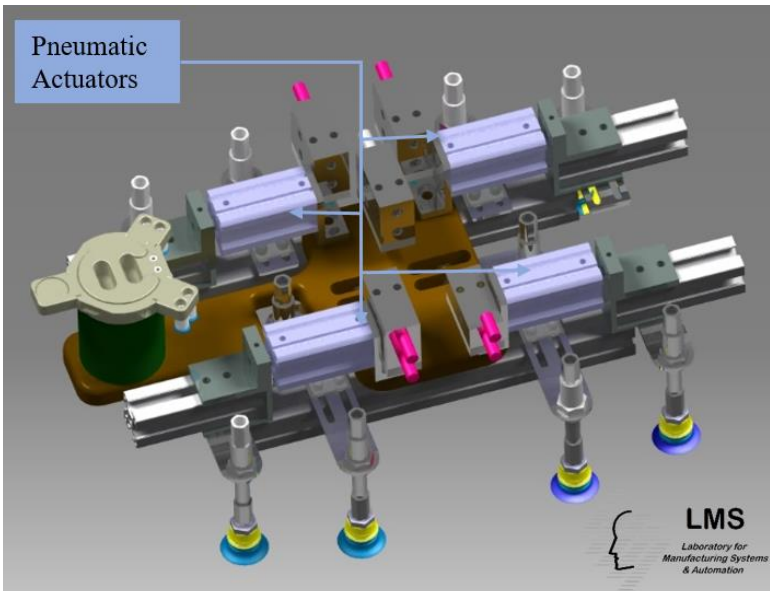


Figure 81: Vacuum gripper pneumatic actuators for length adjustment

Also, a distancer was designed to be installed on the main body of the gripper, to avoid collision between the Wingman tool changer's pressurized air modules and the gripper mechanism during extension and retraction of the gripper's length. The distancer, increases the height of the Wingman tool changer part, and ensures that there is enough separation distance between the telescopic mechanism parts and the tool changer's pressurized air modules. The selected material for this distancer is PVC, in order to keep the overall weight of the solution in low levels (Figure 82).

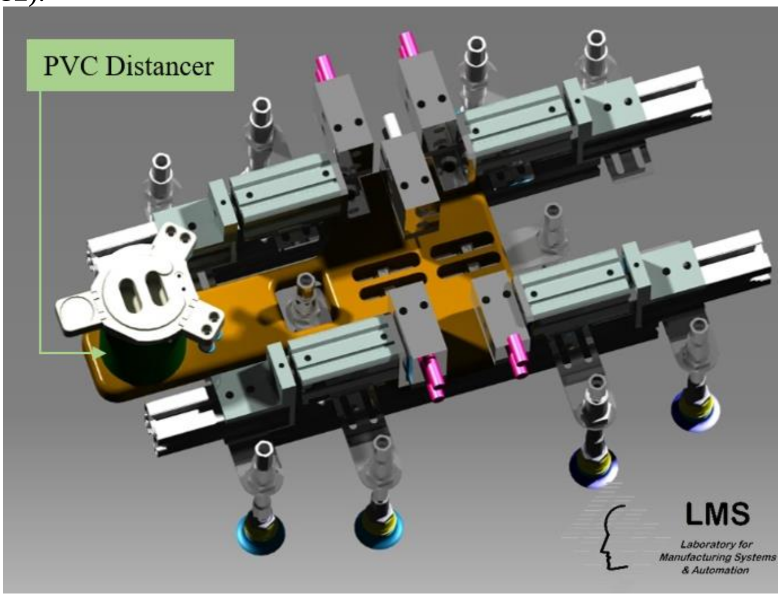


Figure 82: Design of the PVC distancer of the vacuum gripper

Tool changer system:

The Wingman tool changer system [25] has been selected to perform the automatic tool changing, by the UR10 robot, in order to pick and place different parts. The Wingman tool changer system consists of three different parts: a robot part, a tool part, and a tool holder part. The system and its parts can be depicted in Figure 83.

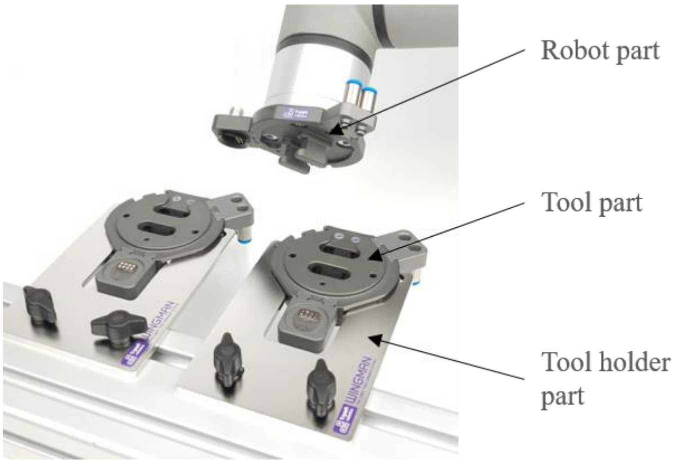


Figure 83: Wingman tool changer system components

Finally, a distancer of PVC material was designed, in order to avoid collisions during the tool changing process. The overall design of the UR10 robot with the camera and the Wingman tool changer with the distancer installed, is depicted in Figure 84.

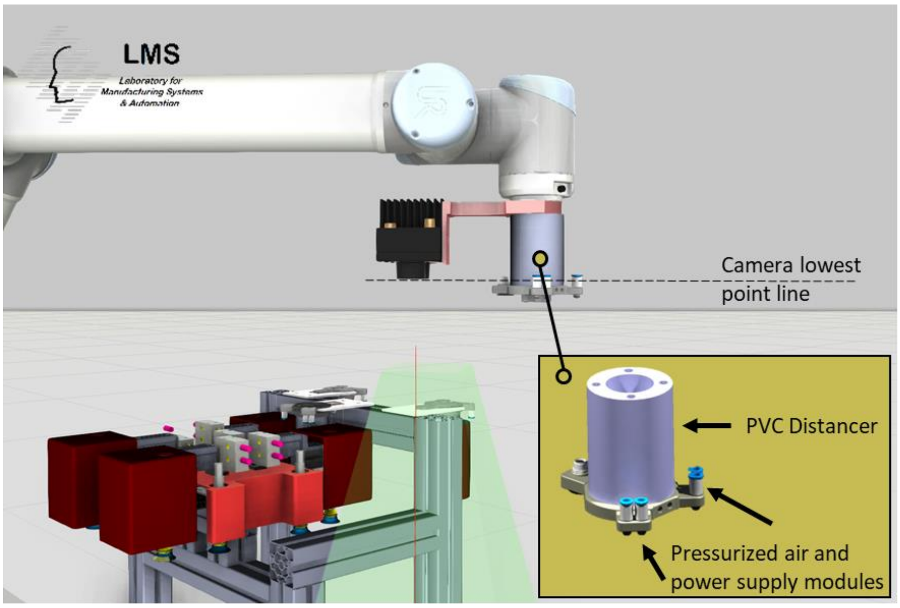


Figure 84: Wingman robot part assembly with the distancer to avoid camera collisions

7.3. Process perception

This section presents the use of perception modules in the White Goods pilot.

Object pose estimation using CAD models

The 3D object pose estimation module will be deployed in the White Goods pilot as an alternative 3D vision system to the currently existing solution. Ideally, the new vision solution should have less constrains in terms of placing of parts and structure of the workspace.

Similarly to other pilot pines, the detection of the microwave components of interest (knobs, cooktops and transformers) has been tested in the simulation environment, as shown in Figure 85 for the knobs.

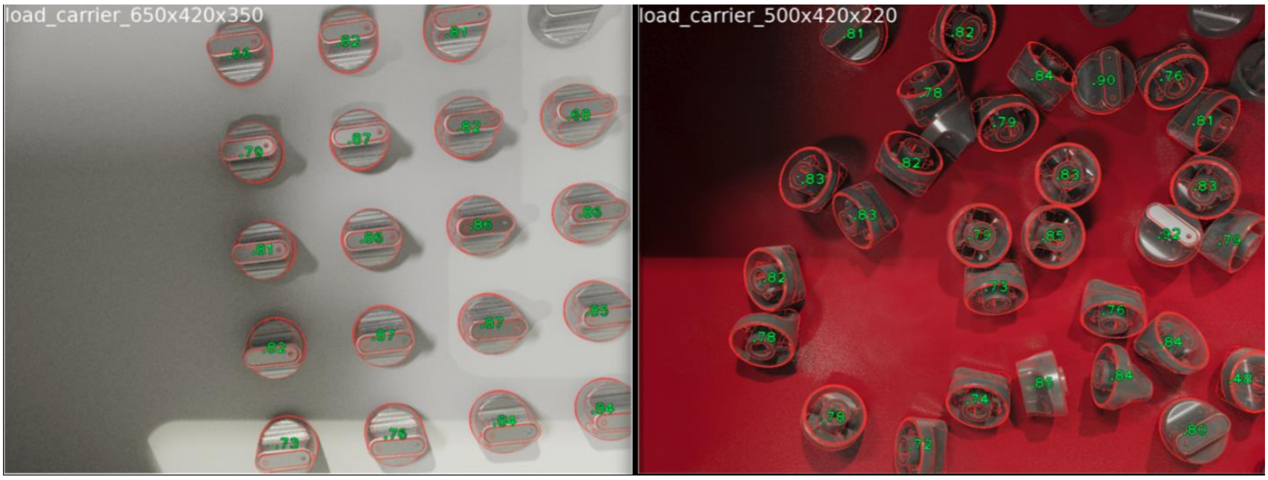


Figure 85: Sample detection results on simulation images. The green number represents the detection score computed by the detection software

The indicative detection ranges for the knob part are shown in Table 11. The current small-scale pilot setup at LMS includes a robot-mounted rc_visard 65m camera.

Table 11: Indicative detection ranges for the White Goods knob object for different sensor models

		rc_visard 65m/c	rc_visard 160m-6	rc_viscore
Min Distance	Z [mm]	200	500	500
	Workspace [mm]	175x180	240x300	233x324
Max Distance	Z [mm]	418	627	1817
	Workspace [mm]	436x376	341x376	1401x1178

The position and rotation accuracy achieved for the same part in the simulation environment is shown in Table 12. The third column of the table shows how the rotation accuracy can be improved if the small object feature that break the symmetry (i.e. the stamped marking on the knob) is not considered. This feature is often difficult to detect correctly when partially or completely occluded (e.g. knob is upside down in the simulation scene).

Table 12: Estimated position and rotation accuracy for the knob object in the simulation test scenes

	Position accuracy [mm]	Rotation accuracy [deg]	Rotation accuracy with symmetry [deg]	Score
Mean	0.637	40.4	3.0	0.879
Standard Dev	0.488	72.3	1.8	0.038
Median	0.506	2.8	2.6	0.889

The vision system is already integrated in the small-scale pilot at LMS and an initial testing of the detection has been performed on all components (Figure 86 and Figure 87).

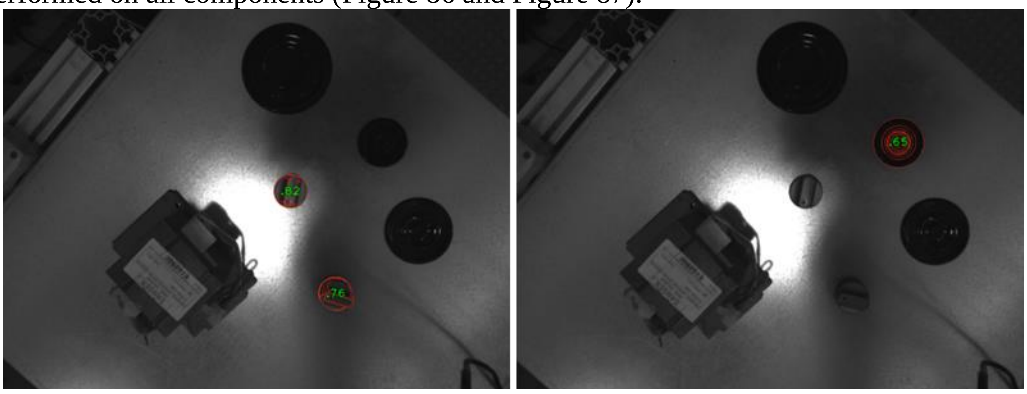


Figure 86: Detection results of knob (left) and small cooktop (right) on recorded images

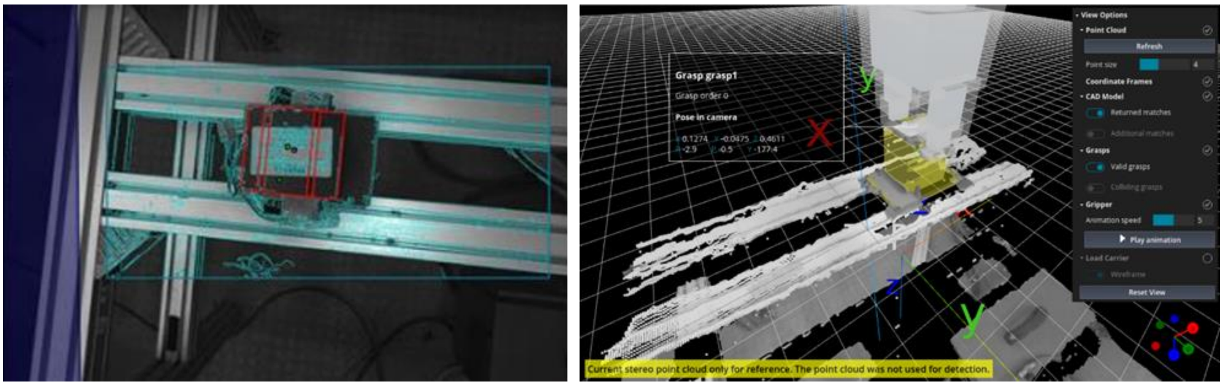


Figure 87: Detection result for the White Goods transformer object in the small-scale pilot setup at LMS (left) and 3D visualization in Web GUI (right)

<u>Human body skeleton and human motion detection</u>

One or multiple RGBD sensors will be installed on top of the HRC work cell calibrated with the robotic system for human body skeleton detection. The calibration method consists of a calibration of the camera and a hand-eye calibration of the robot. Through the calibration procedure, the robot, the human operator and the sensors will share a coordinate system as presented in Figure 88. This calibration process starts with the calibration board, followed by matrix conversion and distortion correction to unify the spatial coordinate systems of the human operator and the robot. Then, the depth images of the human operator captured from the RGBD sensors are fed into the human body skeleton server for recognition. The human skeleton coordinates are obtained from a trained learning model. The original depth image stream is processed by a localisation algorithm and feature extraction. Then, the ideal 3D point coordinates are predicted, which represents the completion of human skeleton recognition. The calibration of the HRC cell and human body skeleton are presented in Figure 89. Based on the previous calibration process, the human skeleton coordinates from the depth map can be extracted by using the human pose estimation method based on the learning method. Finally, the feature matrices of the human body skeleton are defined as the control input to the classification model for human motion prediction in the HRC cell.

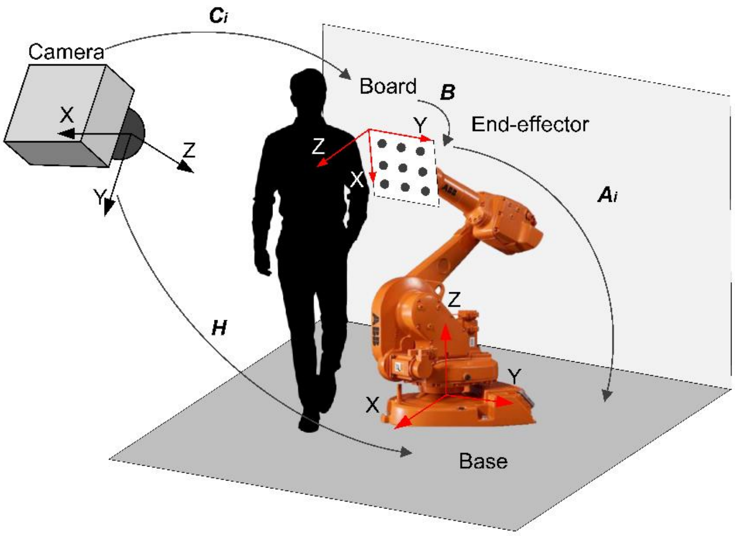


Figure 88: Robot calibration and unification of the world coordinate system

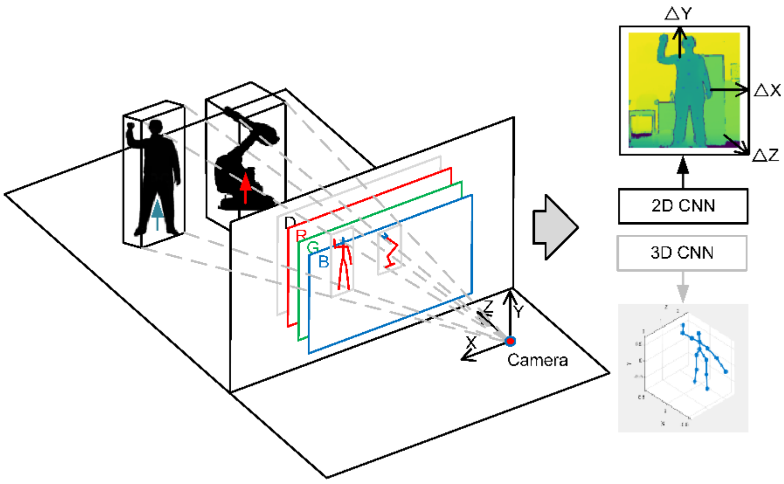


Figure 89: Calibration of the HRC cell and human body skeleton acquisition

Human detection and object localization

The workplace will be equipped with one or multiple RGBD sensor, installed on atop of the cell. The sensor will be calibrated against the cobot's coordinate system, with sensor's point cloud and robot joint coordinates aligned with each other. The system will monitor dynamic area around the cobot and send signal in case operator violates the safety area.

7.4. Safety Related Parts of Control System (SRP/CS)

The components and functions described herein are defined on the basis of the Design-based Risk Assessment and related Safety Concepts described in sections 7.1 and 7.5 of deliverable D5.1 (M18), respectively. Both analysis represents the updates since the preliminary SRP/CS architecture definition included into Section 3.3 of deliverable D1.3 in M9, providing a higher level of detail.

Figure 90 below provides an overview of the architecture of the Safety Related Parts of Control System required for the implementation of the necessary Safety Functions addressed to reduce the risks identified in D5.1 to acceptable limits where reduction by intrinsically safe design measures is not applicable.

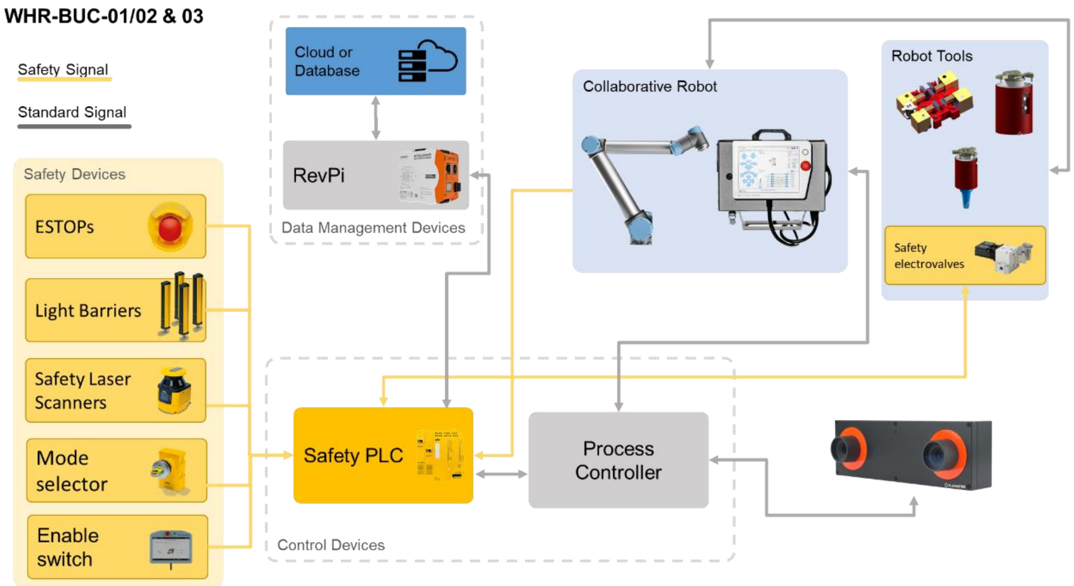


Figure 90: Safety Architecture for White Goods Pilot

The devices conforming the White Goods Pilot Safety Architecture are:

- Safety Controller. A fail-safe PLC or safety configurable relay is introduced in order to manage the safety logic at higher level.
- E-Stop switches, connected to the main safety PLC.
- Light Barriers, addressed to limit the access to the back area of the cell, where the infeed of pallets with components are loaded. They will be directly connected to the main safety controller.
- Mode selector to allow the switch between automatic operation and hand-guiding (for teaching) of the UR robot. It will be connected to the main safety controller.
- Universal Robot UR5 collaborative Robot, which controller fail-safe signals to enable disable operation and emergency stop will be connected to the main safety controller. The collaborative robot is integrating the Power and Force Limiting (PFL) functions in order to work in method 4 stated in ISO/TS 15066 [34]. An enabling switch necessary for the hand-guiding operation of the robot (teaching) is integrated into the robot teach pendant.
- Miniature fail-safe magnetic switch to monitor the attachment of the vacuum gripper.
- Safety electro valves to safely relieve the pneumatic energies of vacuum gripper actuators.

In order to reduce the risks identified in D5.1 to acceptable limits where reduction by intrinsically safe design measures is not applicable, the implementation of Safety functions is required. The following Safety Functions are required for all business use cases related to this pilot (WHR-BUC-1/2/3):

- In order to work in method 4 (PFL), the collaborative Robot must integrate collision detection and **power and force limiting** safety functions available.
- The robot **Safety-Rated monitored Stop (SOS)** function, according to EN ISO 10218-1 5.5, must ensure a correct stop when the collision is detected or when any fault in the safety-rated functions is detected. "Deceleration Monitoring" function is needed to ensure a correct robot stop.
- Robot **Safety-Rated reduced Speed** must ensure a correct slow speed (lower than 250mm/s) of the robot:
  - when working in PFL method., the velocity will be determined and limited so that not exceed the limit values of force and pressure for contact between human and robot, as indicated in ISO/TS 15066 [34]. Limit values will depend on body region where this contact could occur.
  - Working in SSM method, at the back infeed areas, the velocity is determined according to ISO/TS 15066 [34] formulas addressed to avoid the robot contact with the operator, stopping the robot before it occurs.
- **Space limiting Functions** of UR robot are used to define different volume in which the robot axes can move, considering the position and safety of the operation. A movement out of this area must generate a SOS.
  - In this pilot, space limiting is used to:
    - Switch between high-speed robot operation into the back areas not reachable by the operator in normal operation (SSM), and collaborative configuration (PFL) when robot is operating into the reachable area by the operator.
    - safely disable the robot operation into back area side (from 2 total sides) where the light barriers protecting them are triggered, during load of the different infeed areas.
- **Monitoring of vacuum gripper is attached to the robot** shall be implemented. This function will then be used to:
  - trigger the robot SOS function when an operator enters into one or more of the back infeed areas, as this tool is not designed for PFL method. That event will also trigger the **pneumatic pressure relieve.**
- As required by ISO/TS 15066 [34]**, mode selection** function is required in order to switch between robot AUTOMATIC mode and HAND-GUIDING. Any operating mode change should trigger a SOS in the Robot, and automatic operation restart needs to be prevented.
- **3-way position switch** must be used to enable the Hand-Guided operation of the robot. The release of the enabling device and/or an excess of pressure on the device must generate a SOS in the Robot.

- Robot **Hand-Guiding function** must ensure that only actuations of the HG device (impedance and gravity compensation control) can generate Robot motion. Motion of pending movements, orders of other robot programs, and any other input are avoided.
- **Light barriers** on the two infeed zones at the back of the cell enable the robot safety configuration switch from high-speed to PFL (except when vacuum gripper is attached), and restricting its operation into the accessed area.
- **ESTOP Push-Buttons** and **ESTOP Rope** stops all the actuators of the machine instantaneously and disables all the power supplies (electrical, pneumatic, etc).
- Any fault or malfunction of the safety-rated functions must generate a Safety-Rated monitored Stop.

In general, the required performance level for the safety-related control system above described is PL "d" category "3" according to EN ISO 13849-1 [33]. This level is stipulated by standard type C EN ISO 10218-1 (in section 5.4) for robots and robotic systems.

The above-described safety functions are the most representative for the business use cases explored in ODIN. This list may be complemented with additional functions necessary for real production operation. The above-described functions have been identified in a preliminary design stage of pilots (based on simulations, CAD models, etc.) and in line with Design Risk Assessment presented in D5.1. After future onsite Risk Assessment on real pilots, additional risk reduction measures may be requested, thus affecting future design and/or Safety Related Parts of Control Systems (SRP/CS). More details on the safety concepts where these functions are applied as risk reduction measures, as well as the details of the required performance level according to ISO 13849-1 [33] can be found within deliverable D5.1.

8. CONCLUSIONS

This document has presented the current design and implementation of ODIN core enabling technologies.

The selection of autonomous mobile and robotic manipulators and their deployment to the ODIN pilot has been described, together with the required customizations currently in progress.

The tooling is designed and chosen, to ensure grasping safety during parts' manipulation in ODIN human – robot collaboration pilots. As described, safety is a key factor in the design of the robot grippers as it ensures uninterrupted human-robot collaboration and robot-to-robot collaboration in physical terms, and also ensures safe manipulation of the parts, minimizing the possibility of an accident, or a failure to grasp a part. Also tooling reconfigurability was taken into account to ensure versatility in grasping possible part variations, with relatable geometric and material properties for each gripping solution.

The skills required for robotic perception of environment, process and human cover many different research domains, going from 3D object detection based on CAD models to human body skeleton detection. For each module, this document has provided an overview of the required hardware, the designed software interface and the prototypical implementation, that will be extensively tested and enhanced in the next months of the project.

The work presented in this deliverable is work in progress, and the descriptions here presented might be modified, enhanced or improved during the development time of WP2 and the relevant tasks in this work package. The final version of the presented prototype technologies will be documented in D2.4 which is planned to be submitted on M36.

9. GLOSSARY

AGV	Autonomous Guided Vehicle
AMM	Autonomous Mobile Manipulators
AR	Augmented Reality
AVI	Automated Visual Inspection
ASF	Automotive Smart Factory
ES	E-Stop
FC	Fan Cowl
GUI	Graphical User Interface
PDL2	Comau robots programming language
PID	Proportional Integrative Derivative (control)
PLC	Programmable Logic Controller
PL	Performance Level
PLr	Performance Level requested
RGB	Red Green Blue sensor
RGBD	Red Green Blue Depth sensor
ROS	Robot Operating System
SDF	Signed Distance Fields
SRP/CS	Safety Related Parts of Control System
TCP/IP	Transmission Control Protocol / Internet Protocol
TSDF	Truncated Signed Distance Fields
UI	User Interface

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