Chapter 3

Robotic Systems for Removing Asbestos

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Bots2ReC Robots to Re-Construction

Funded by the European Union

3.1 First Robotic Prototype (V1)

3.1.1 Mobile Base

Deliverable i2.1
Di2.1 Specifications and design concepts for mechatronic stabilizers

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3.1.2 Deliverable in the Context of the Work Program

The deliverable D2.2 takes input from *Task 1.2 – Initial trials of operational process*, *Task 2.1 – Preliminary simulations of the robotic units and Task 3.2 – Definition of technical requirements for the customization*.

For this deliverable D2.2, static and dynamic stability requirements that will not be fulfilled by the standard base platform are investigated and a concept for mechatronic stabilizers will be developed. The static requirements refer to the tilting limits of the platform due to gravity in the different arm and tool states. As the speed and acceleration of the platform will be low, the dynamic requirements will expectably not be critical regarding tilting and overturning limits. However, the forces to be exerted by the robot pressing the tool against the walls at all possible heights affect the robot stability. The standard way to cope with stability problems for civil engineering machines is to use landing gears. In the context of construction machinery, landing gears are a kind of stabilizer legs that are deployed to increase the platform stability. In this case, those devices must be modified for indoor use and taking advantage of contact points not exclusively located on the ground (walls, ceiling). The designed system should compensate the tooling forces against the walls during the removal operations and also the dynamic forces during locomotion / arm repositioning evaluated in task 1.2 and 3.2. The work requires evaluating a global stability criterion during asbestos removal and specifying mechatronic stabilizers (D 2.2):

- Choice for a suitable stability margin (static, dynamic) and the associated sensors (e.g. measurements on geometry, force pushing)
- Dynamic modelling for efficiency assessment based on the existing simulations from task 2.1 and further co-simulations:
  - 3D virtual model in statics and dynamics
  - Multi-body modelling with calculation of the stability margin during the task
  - Associated control methods
  - Specification and research of concepts for mechatronic stabilizers with a low number of DoF, stabilizing the robotic units against the solid environment (e.g. pushing against the ground or ceiling or attaching to a wall).

A tall (comparable to the kinematic dimensions from tentative dimensioning in section 1.4.4) robotic arm will be considered for preliminary evaluation. A virtual environment will be reconstructed from a digital map of the testing area and additional attributes from task 1.1 to represent the spatial dimensions of the scenario. The simulations are executed parallel to the initial trials of the operational process in task 1.2, to allow modifications and enhancements of the simulation at an early stage.

This deliverable has outputs to tasks 2.2, 2.3.

3.1.3 Methods and Work Carried Out

An extensive study on stability margins can be found in [Garcia *et al.*, 2002] and [Chebab, 2013]. As our robotic unit V1 should be slow and with no particular long dimension with respect to the others, a quasi-static stability margin criterion described for the first time by [McGhee and Frank, 1968] was used. For future work at higher speeds, the ZMP (Zero Moment point) criterion [Sardain and Bessonnet, 2004] could be used as well as non dimensional criteria such as the LLT (Lateral Load Transfer) indicator [Bouton *et al.*, 2007], that can be easily extended to the front direction.

The expression of the LLT can be found in equation (Equation 3.1), where F_{n1} and F_{n2} are the normal forces applied on the left and right sides of the vehicle. When the LLT equals to 1, the robot is at its stability limit, although a value of 0.8 or 0.9 should never be exceeded for safety. When the LLT exceeds 1, the two wheels on one side of the robot lift off and the robot can rollover. This non-dimensional margin is very convenient to use, provided the normal forces are measured by suitable force sensors in the wheel hubs or calculated by the multibody model.

$$LLT = \left(\frac{F_{n2} - F_{n1}}{F_{n2} + F_{n1}} \right) \tag{3.1}$$

The visit organized by Bouygues in a flat that had been cleaned (Clermont-Ferrand, 01/06/2016) confirmed the fact that pushing against the ceiling seems feasible in many cases, at least in apartments and less in offices. For the flats located on top of a building, pushing under main beams is recommended, although beam detection might be tricky. Pushing against thin walls (particularly gypsum plates) is not recommended, so a map of the walls that can serve as a support should be provided to the robot before cleaning. The door frames often provide a strong structure on which a stabilizer could push, provided the paint is kept intact.

3.1.4 Specifications and Design Concepts for Mechatronic Stabilizers

3.1.4.1 Central Stabilizer Pushing on Ceiling

This concept of central stabilizer (Figure 3.1) is extremely interesting as is applies a vertical force to all the wheels, thus transforming the unilateral contact between the wheel and the ground into a bi-lateral contact, much safer. The dispatching of the forces on all the wheels is difficult to model and can change instantaneously with a quasi-null displacement, depending on the degree of overconstraint of the wheels (suspension mechanism, deformable chassis, etc.).

A proposed implementation of the central stabilizer is a vertical jack, actuated by screw, capable to extend to the altitude of 3 m, and equipped in its end by a rubber bushing supporting a pushing plate. The rubber bushing is similar to the fixture that fixes the mast of a windsurf rig to the windsurf board. It is kinematically equivalent to a spherical joint but provides three translational and three rotational stiffnesses: the vertical translation decreases the pushing stiffness of the device, avoiding to

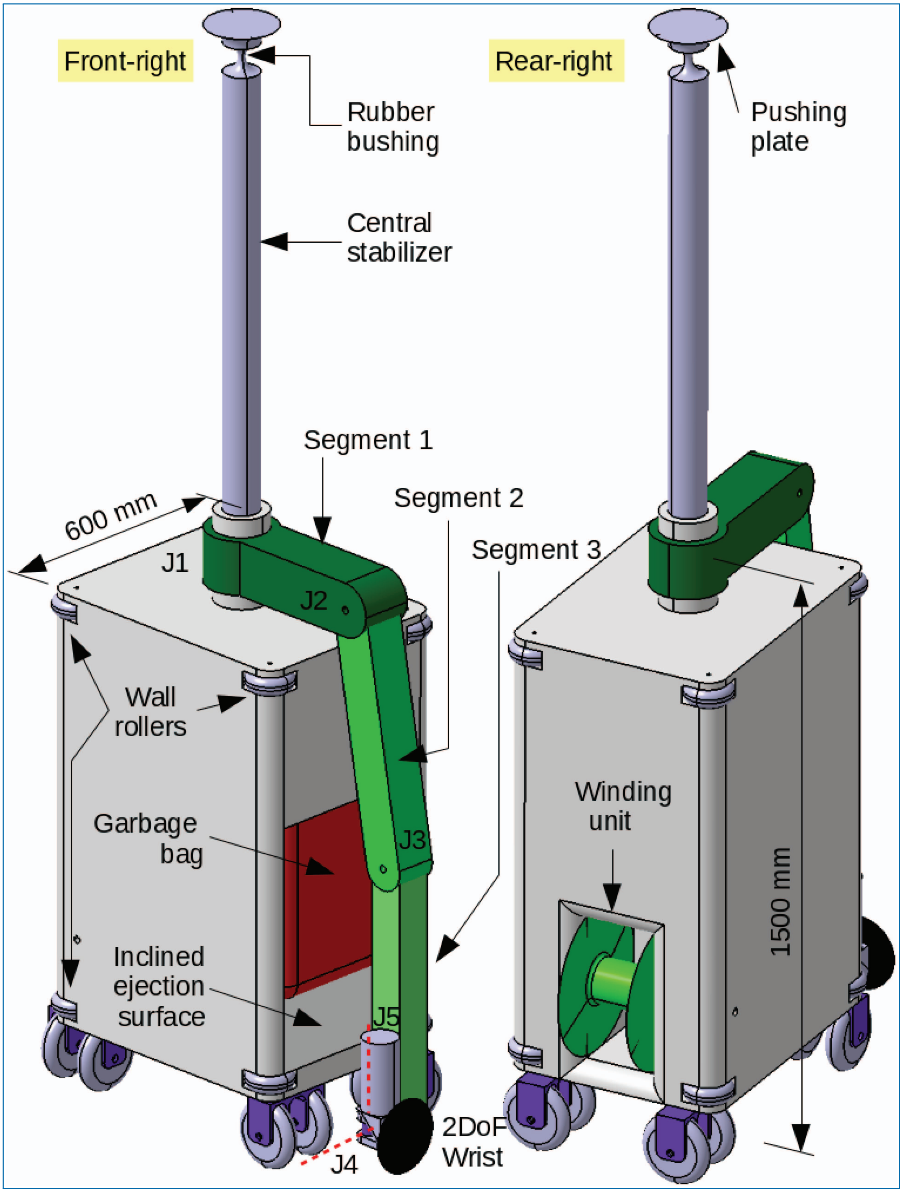

Figure 3.1. CAD preliminary implementation of the robotic unit with a central stabilizer, a winding unit and a garbage bag.

mark the ceiling too much; the rotational stiffnesses maintain the pushing plate towards the top whereas authorizing small rotations if the ceiling is irregular or not parallel to the ground. The pushing plate should be cushioned or made in a sufficiently soft material, with smooth edges, in order that a non-centered pushing force does not make a decentered mark on the ceiling.

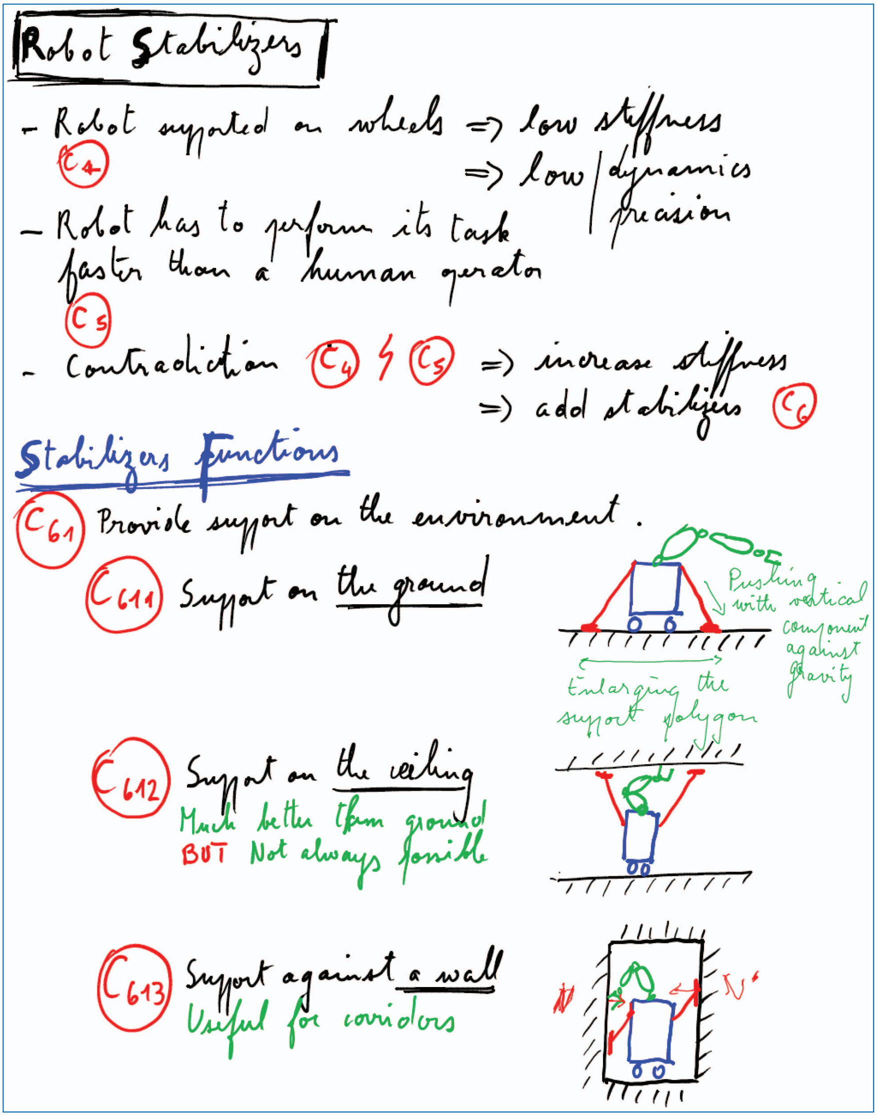

Figure 3.2. Brainstorming about stabilizer functions (Aachen meeting, 17/02/2016).

Obviously, pushing on the ceiling may also be forbidden in certain cases (weak ceiling, fake ceiling...) so this proposal for prototype V1 must be completed by other solutions for prototype V2.

3.1.4.2 More Advanced Stabilizers Concepts

In order to design suitable stabilizers, all the uses case had to be defined and specified. A brainstorming session in Aachen (Figure 3.2) permitted to classify the stabilizer functions.

3.1.4.3 Stabilizers Concepts for Cooperative Tasks

The considered cooperative tasks CT_i at the moment are the following:

- CT0. Several robots working separately in the same room with cable management
- CT1. Cancelling dynamic effect by opposite motions (arms or rotating tools)
- CT2. Manipulating large tools with dual / multiple arms
- CT3. Extending support polygon ? better stability
- CT4. Collaborative obstacle crossing
- CT5. Collaborative cable management
- CT6. Collaborative garbage manipulation
- CT7. Collaborative tool changing
- CT8. Multi-arm tasks: scratching / tearing / observing

The green scenarios are priority in this project. The other scenarios will be developed if enough time remains.

A proposition for CT1 and CT3 can be seen in Figure 3.3, where the stabilizers serve both for connecting two mono-robots to each other, thus forming a poly-robot, and to enlarge the supporting polygon of this poly-robot, which considerably enhances its stability without requiring any assumption on a strong ceiling above. Combined with the concept of dynamic balancing of antagonist arm motions, the resulting poly-robot may succeed in a considerable decrease of its tangential forces on the ground. The distance between the mono-robots should be calculated in order to avoid collision of the two respective arm workspaces without letting an uncleaned band between them. Similarly, the robots can be combined in a group of three for covering corners efficiently and increasing the support polygon in two directions at the same time.

An integrated proposition of a top module regrouping two stabilizing legs can be seen in Figure 3.4. The feet can be locked in suitable locking areas of a neighboring robotic unit for strong attachment between units. The legs can also be controlled for obstacle crossing, a requirement that is not covered at the moment by prototype V1. The axi-symmetric setting of the top module allows connections of the legs in any direction, either with another robot or with the environment.

3.1.5 Implementation of Testing Stabilizers for V1 Prototype

For the testing of first prototype, simple manual stabilizers will be implemented to have a back-up against unpredicted instability scenarios. In this report, initial ideas for implementing manual stabilizers are proposed.

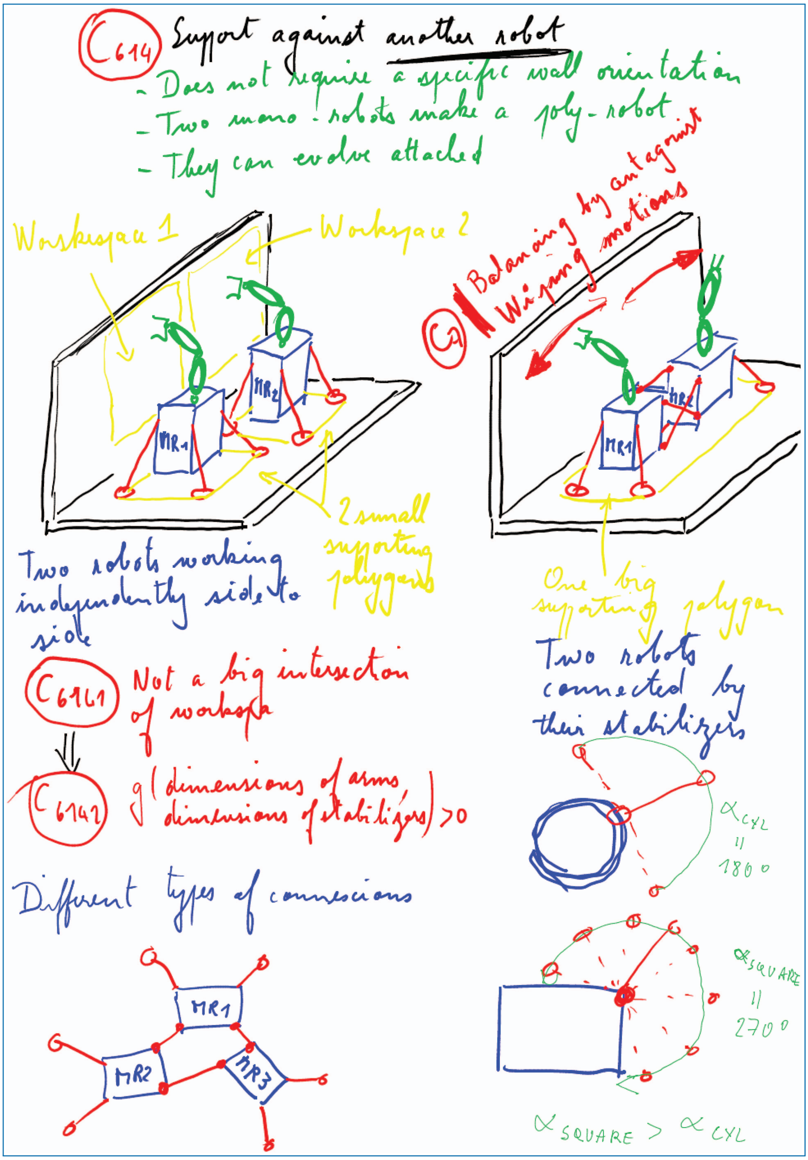

Figure 3.3. Concept of using stabilizers for cooperative tasks.

Requirements on Stabilizers

1. The first and the most important requirement is to increase the support polygon and hence the stability of the robotic unit.
2. Stabilizers should be capable of bearing the load of the robotic unit, as well as the forces/ torques disturbing the stability of the robotic unit.
3. Stabilizers pushing against the ceiling such that the mobile platform bears the pushing load are not allowed.

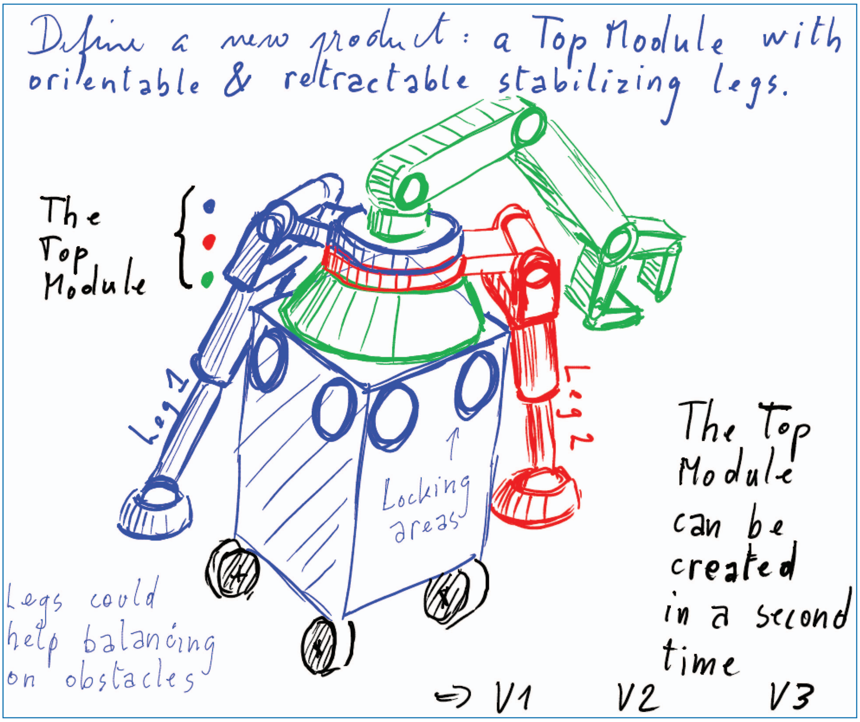

Figure 3.4. Concept of a top module regrouping the attachment points for two stabilizing legs and their power supply and control box. This module can be considered as an additional equipment.

4. After integrating with the robotic unit and in the retracted position, constraint on the overall size of the robotic unit should be respected.
5. Stabilizers should be as light as possible so as to follow the constraint on the overall weight of the robotic unit.
6. Stabilizers should not interfere with the operating robotic arm.
7. Stabilizers should not interfere into the positioning of the mobile platform w.r.t the wall.
8. Stabilizers should allow cleaning in the narrow corridors.
9. Stabilizers should be suitable for performing collaboration scenarios.

Keeping the above requirements in mind, few stabilizer architectures are proposed below.

Few key points on which the design of the stabilizers will be based are:

1. Position (attachment point) of the stabilizers on the robotic platform
2. Kinematic architecture of the stabilizer
3. Determining the resting points of stabilizer legs on the ground and ceiling

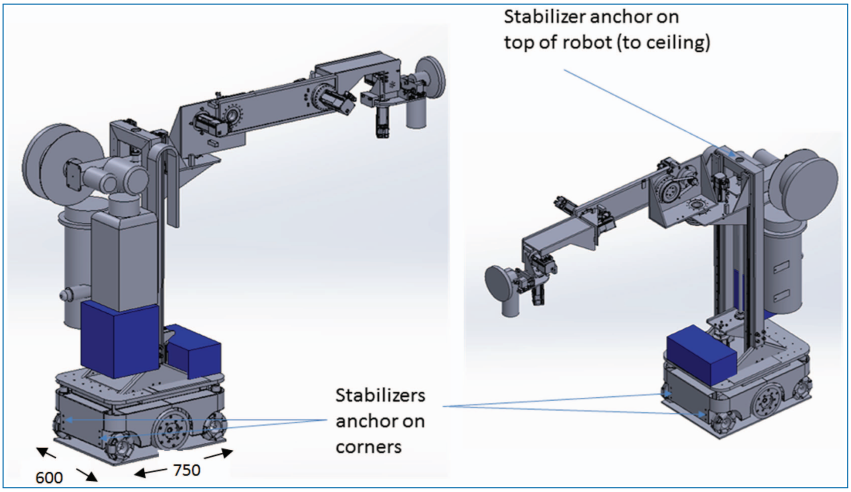

Figure 3.5. Attachments points for stabilizers.

3.1.5.1 Attachment Points of the Stabilizers on the Mobile Platform

In the current mock-up of the robotic unit, the attachment points are identified as above. There are in total 5 attachment points; one at each corner of the robotic unit plus one on the top plate of the vertical slider. However, as pushing on the mobile platform is not recommended, implementation of the vertical slider is doubtful. This allows us to put 4 stabilizers, one at each corner of the mobile platform.

3.1.5.2 Initial Proposition of Stabilizers

In this section, few ideas regarding the kinematic architecture of the stabilizer are proposed. The ideas are mostly concerning the implementation of the manual stabilizers.

Proposition 1: Out trigger Stabilizers

Figure 3.6. Example of outtrigger stabilizers.

- The kinematic architecture of the stabilizer consists of two prismatic joints. This simple architecture will serve as good option for the testing of first prototype.
- There is of course, a limit on the achievable extension of the horizontal prismatic joint which determines the increase in the support polygon.
- According to the dimensions of the mobile platform, we have a rectangular support polygon of the size approximately **600 mm × 750 mm**.

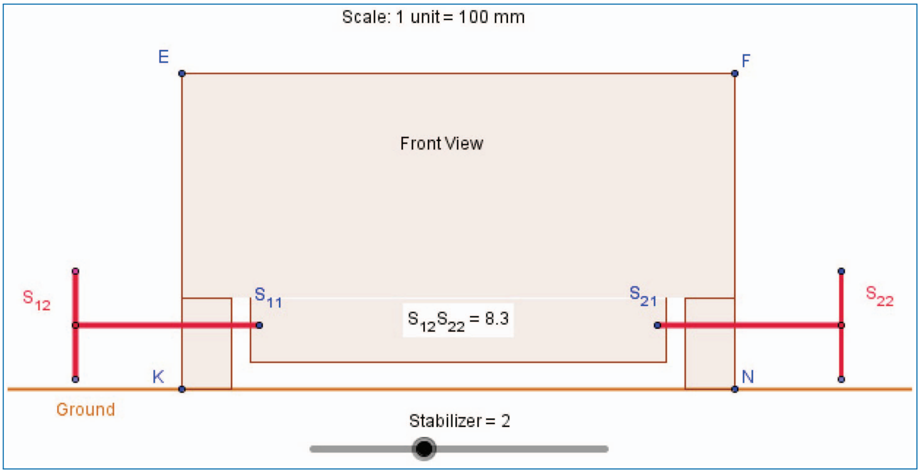

Figure 3.7. Extended pose of the stabilizers.

From Figure 3.8, it is clear that, for avoiding collision, the maximum retraction length on stabilizer is around 200 mm. This puts a constraint on the maximum length of extension (unless we design a telescopic structure). Distance $S_{12}S_{22}$ indicates the total distance between the two points on the stabilizers which is 830 mm approx. Thus, the width of the new support polygon is increased by 230 mm.

Proposition 2: Rotating Stabilizers
The kinematic architecture of this type of stabilizer is Revolute-Prismatic. The stabilizers are attached to the mobile platform using revolute joint; for e.g the stabilizer link $S_{11'}$–$S_{12'}$. At point $S_{12'}$, there is a prismatic joint perpendicular to the link to ground the stabilizer. The maximum length of the stabilizer links can be 600 mm. Links $S_{11'}$–$S_{12'}$ and $S_{32'}$-$S_{12'}$ define new support polygon.

Figure 3.10 shows the folded position of the stabilizer, thus satisfying the constraint on the overall size of the robotic unit. For avoiding interference in the folded

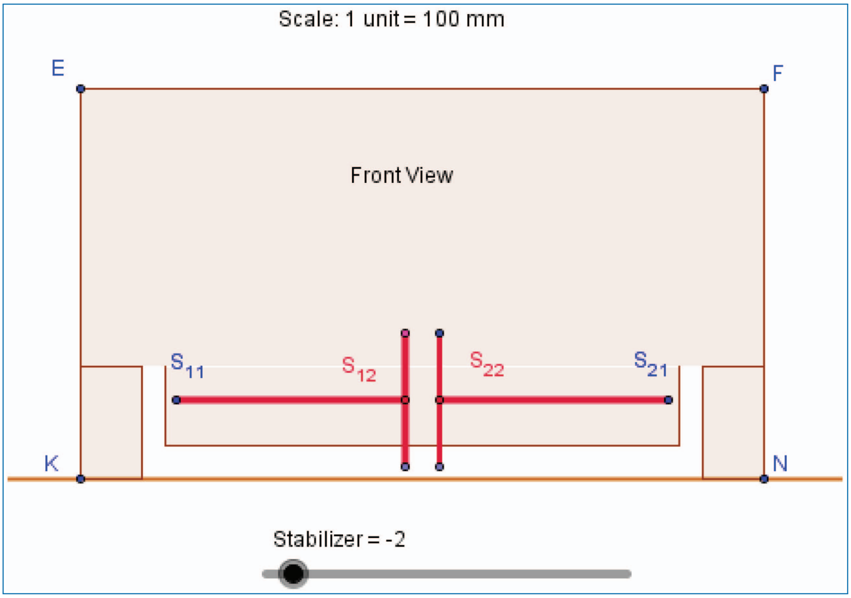

Figure 3.8. Retracted pose of the stabilizers.

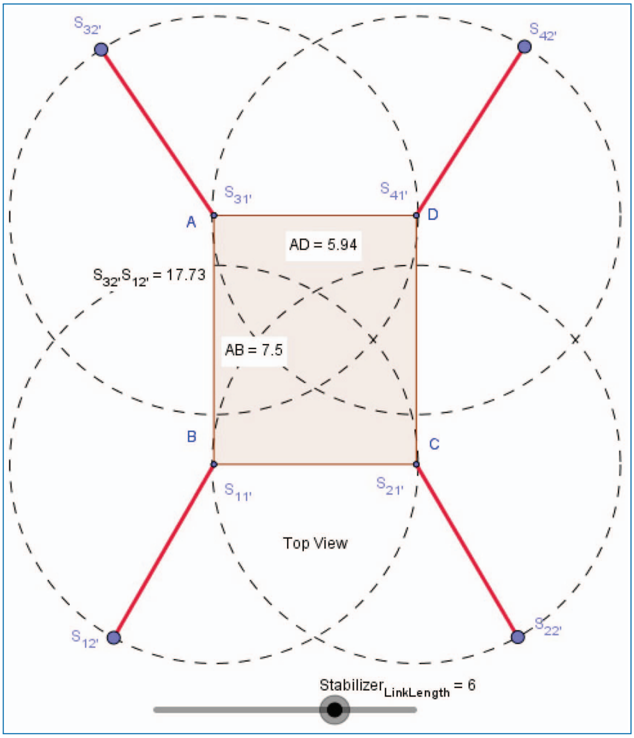

Figure 3.9. Stabilizers extended position.

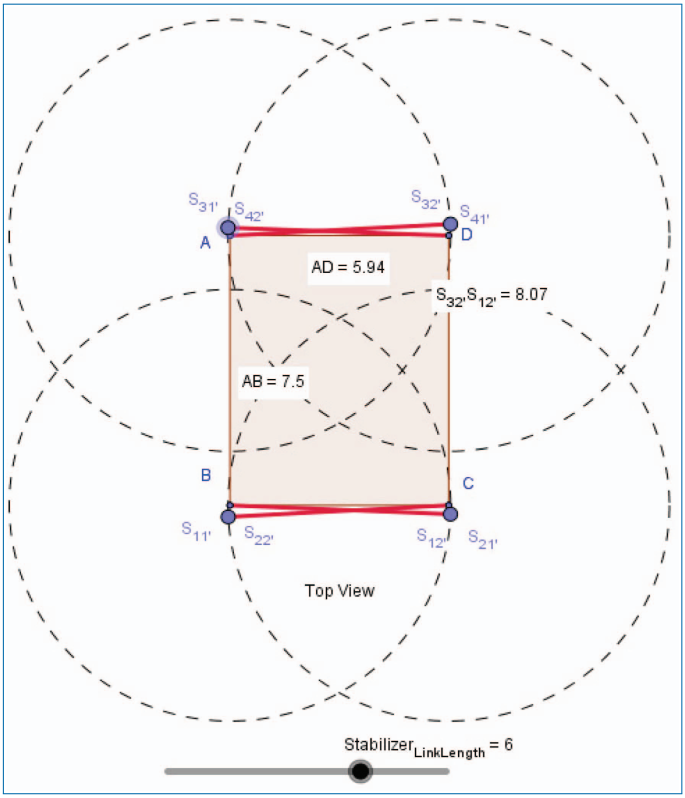

Figure 3.10. Stabilizers retracted position.

position i.e. to enable folding of stabilizers, the two front/rear stabilizers can be fixed at different altitudes on the two corners of the mobile platform. The long link lengths will allow more increase in the support polygon.

Proposition 3: 2-R Stabilizers
Here, the kinematics of the stabilizers is consisted of 2-R architecture as shown in Figure 3.11.

By considering the factor of safety as 1.3, the width of the extended support polygon will be 850 mm approx. i. e addition of 130 mm on both sides. The link lengths of the stabilizers are determined based on this requirement on reachability as 160 mm each.

3.1.5.3 Antagonist Pushing

The central vertical stabilizer installed attached to the top plate of the vertical slider will exert extra efforts on the mobile platform while pushing on the ceiling. This

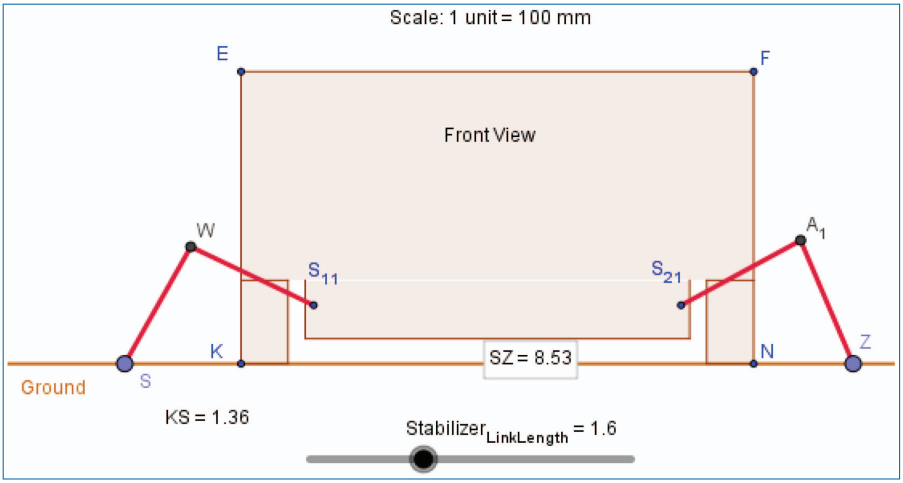

Figure 3.11. Stabilizers working position.

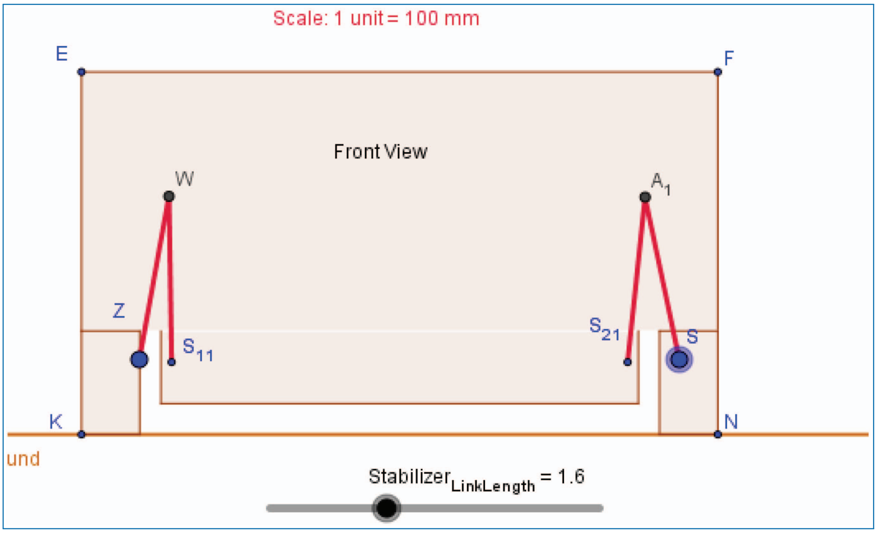

Figure 3.12. Stabilizers retracted position.

may damage the mobile platform as it is not designed for this extra effort. Thus to achieve the pushing against ceiling without putting extra load on the mobile platform, an idea of antagonist pushing mechanism in proposed. The two prismatic joints will act opposite to each other pushing on the ceiling and the ground simultaneously. Figures 3.13 and 3.14 show the pairs of antagonistic pushing links (Links: WE_1-WD_1 and A_1G_1-A_1F_1).

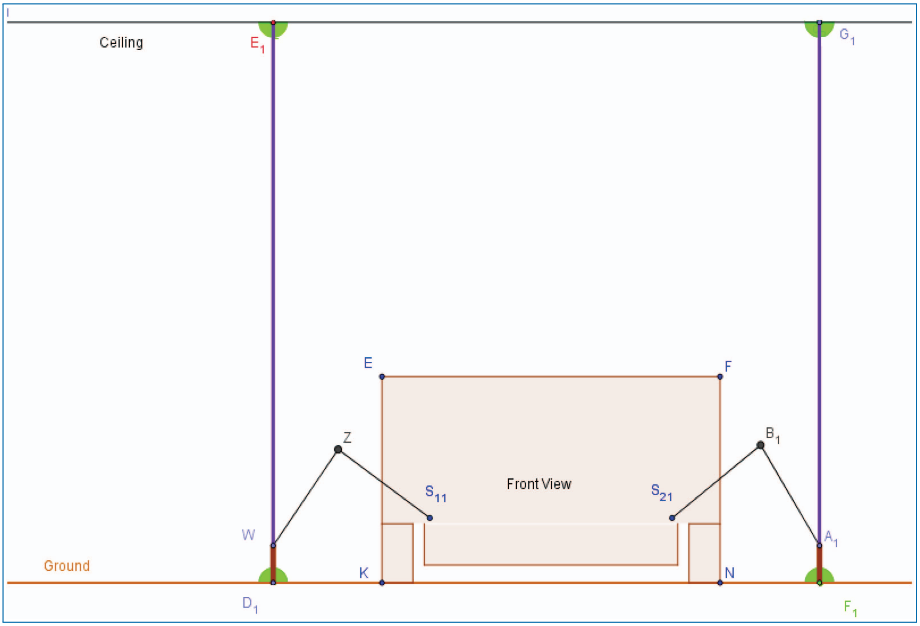

Figure 3.13. Antagonist pushing in 2-R architecture.

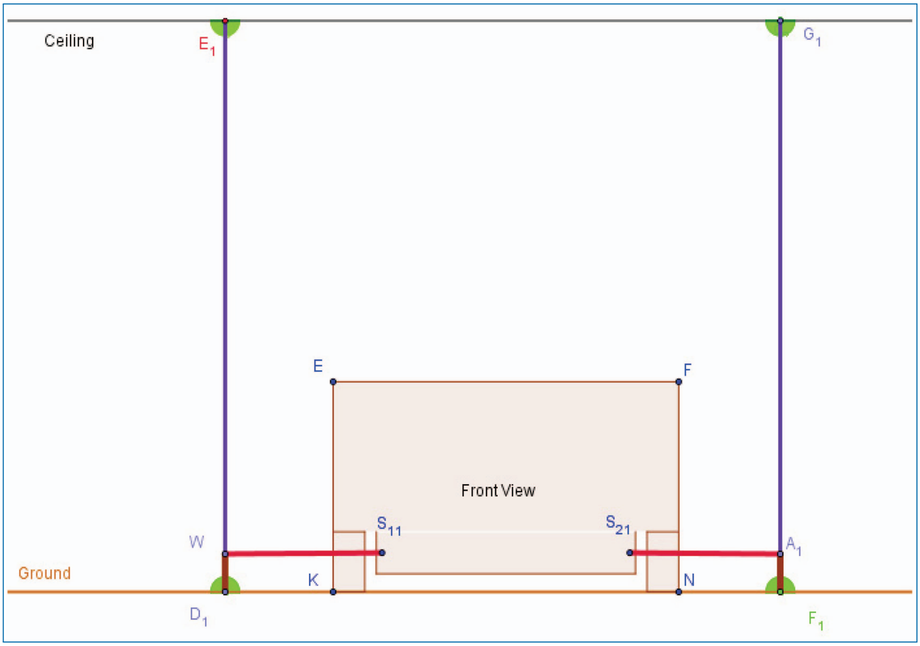

Figure 3.14. Antagonist pushing in outtrigger and rotating stabilizer architecture.

CAD Model of the Robotic unit equipped with stabilizers

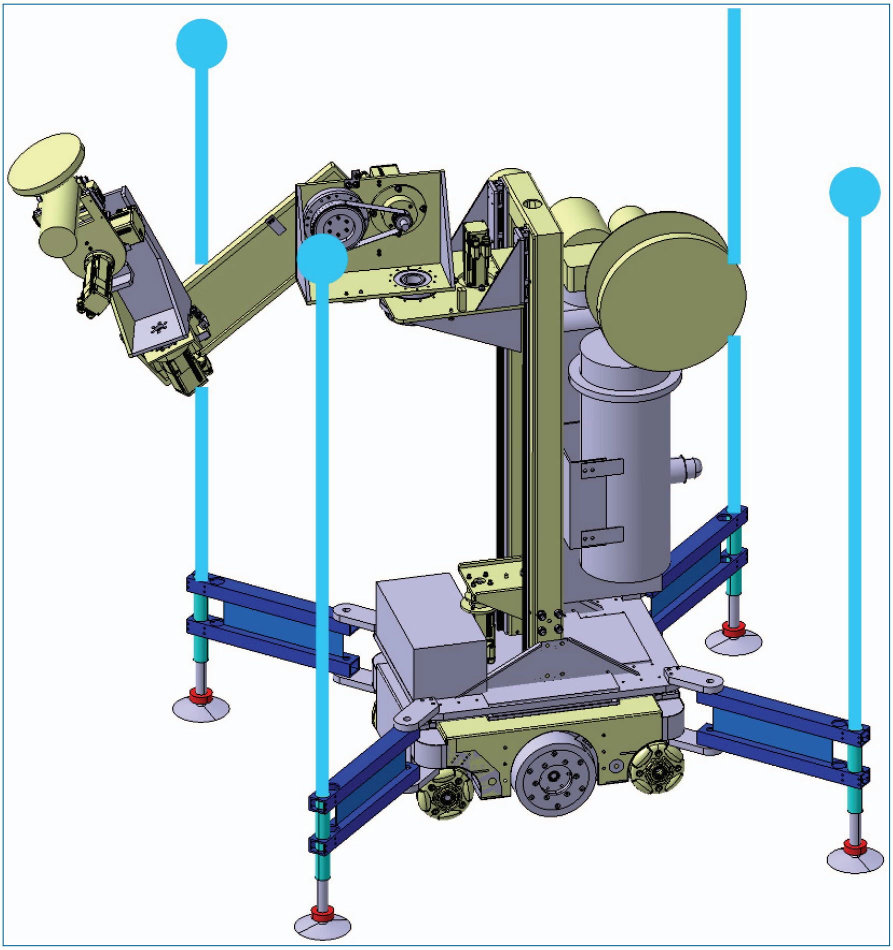

Figure 3.15. Antagonist pushing in rotating stabilizer architecture.

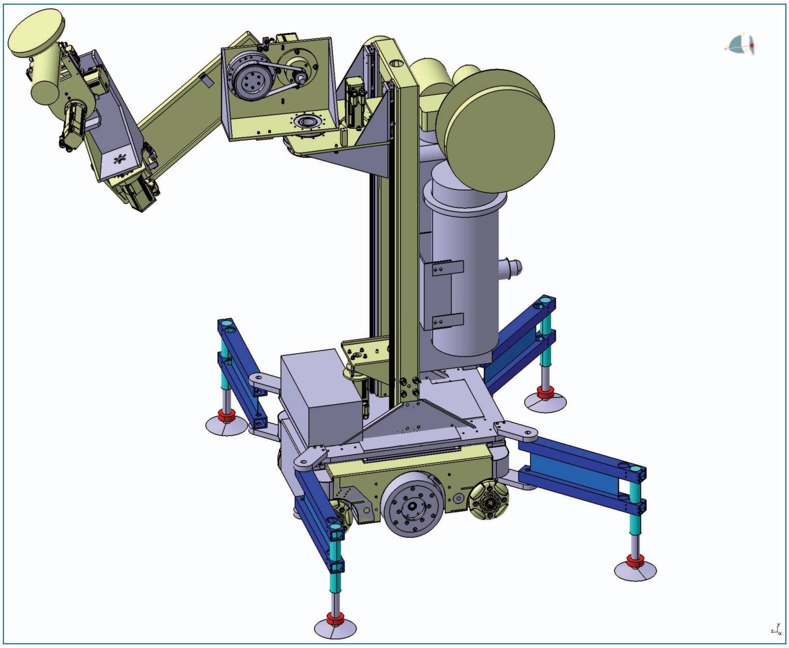

Figure 3.16. Flat alignment of front stabilizers for getting closer to the wall.

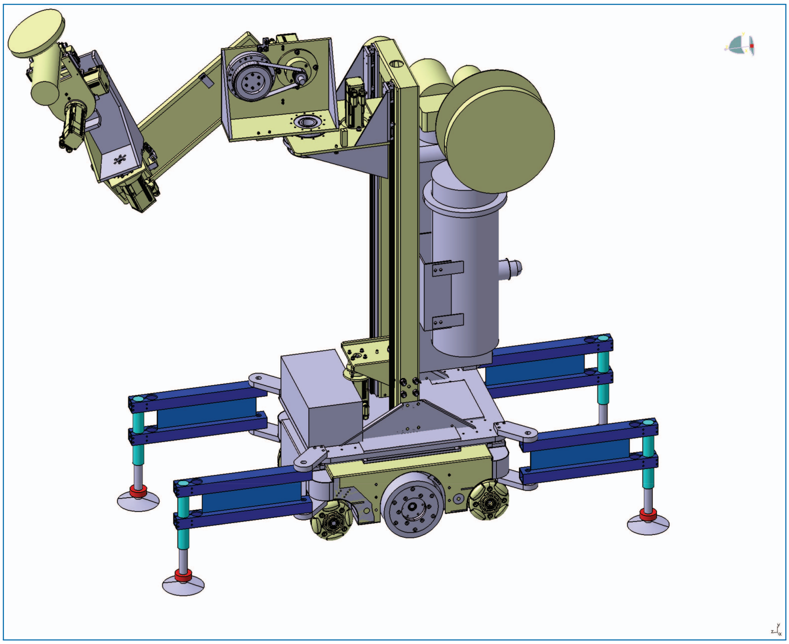

Figure 3.17. Alignment of stabilizers in narrow corridors for frontward cleaning.

3.1.5.4 Resting Points for Stabilizers

Resting points will define the contact between each stabilizer leg and ground. Resting points are nothing but contacts points between stabilizer legs and ground. They will define a new support polygon larger in dimensions than the one defined by wheel contact points of the robotic unit. This will give us the increased stability. Thus, the dimensional synthesis of the stabilizers is closely related to the assessment of stability as well as productivity of the robotic unit without stabilizers. Stability margin required in the worst case instability scenarios will lead us to the dimensional synthesis of the stabilizers. Similarly, stability margin expected in other unstable cases will determine the resting points for stabilizers. This will be determined through dynamic simulation of the cleaning process.

3.1.5.5 Collision Between Stabilizer legs and Robotic Arm

Stabilizers are deployed in the workspace of the robotic arm and thus there are occasions where robotic arm can collide with the antagonistic pushing links. This is realized using Geogebra models presented in Figure 3.18. This figure shows a top

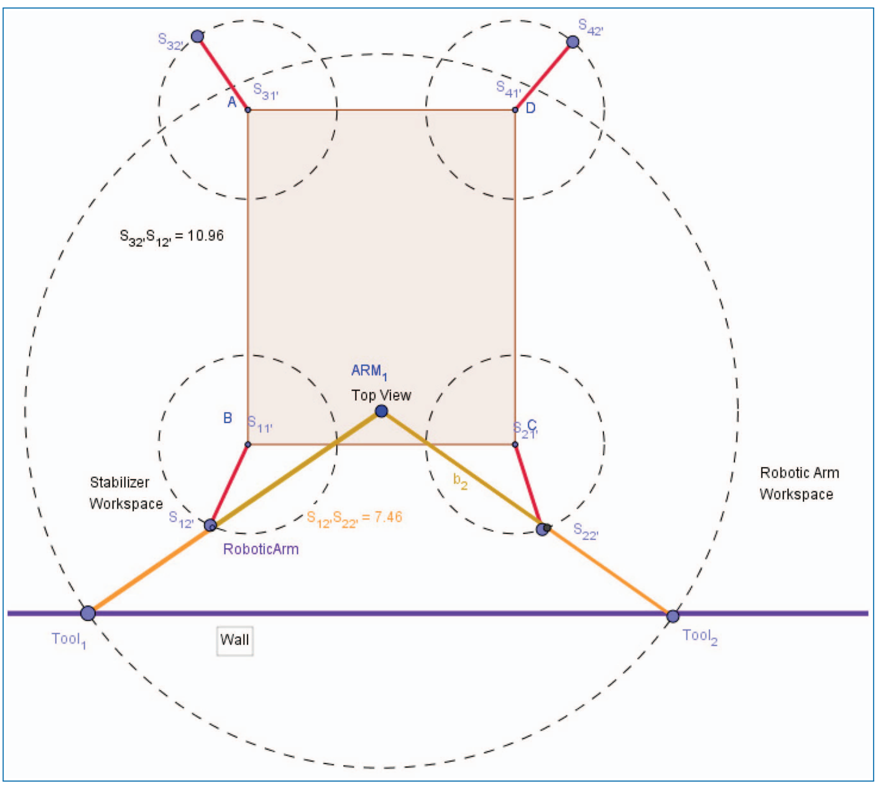

Figure 3.18. Collision between robotic arm and stabilizer.

view of the scenario where robotic arm is colliding with the antagonistic pair of the stabilizers. Thus, while determining the resting points for stabilizers, the scenarios of collision must also be considered.

3.1.5.6 Outlook and Future Work to be Carried Out

All these concepts require to be prepared and integrated into the CAD mock-up of prototype V2. They will be further developed during the next year, as this second prototype is only expected for month #30. They will strongly benefit from the experience and feedback to be expected from prototype V1, particularly for characterizing the dynamics, contacts and external forces of the real robot. The stabilizers will also serve to implement several collaborative scenarii listed in §3.3 within Task 2.4.

3.1.5.7 Summary and Conclusion

This deliverable is still under progress because all the dynamic data have to be confirmed by experimental tests. Several models for quasi-static stability have been constructed and provide encouraging results: overall, all our robotic units are stable within their complete workspace for slow motions, without any tool effort, for light terminal segments of the arm and without stabilizers. A proposition of a central stabilizer pushing against the ceiling has been made, which provides a good stabilization and transforms the unilateral contacts of the wheels on the ground into much safer bi-lateral contacts, because the robot cannot lift its wheels any more. However, because of limitations on the load bearing capacity of the platform, the real implementation of this system will be made into prototype V2. The proposition for V1 can be seen in figure 16, with four stabilizers providing antagonistic pushing against ground-ceiling.

Future work in task T2.2 will cover the structural and dimensional synthesis of advanced stabilizing legs serving both for stabilization and multi-robot interconnection for five collaborative scenarii. This is compatible with the expected planning for prototype V2 (30 months after the project beginning).

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Deliverable Di3.2
Di3.2 – Specification of the technical Requirements for the V1 prototype
Part B – System Specification

Authors: Daniel Martin

3.1.6 Deliverable in the Context of the Work Program

The present *Di3.2 – part B – System Specification* reports the technical specifications for the V1 prototype carried out by the BOTS2REC Consortium during the first months of the Project. The system specifications are detailed in the following sections of the document and complemented with the control architecture definition and the identification of interfaces included in the deliverable *Di3.1 – Specification of the system architecture and interfaces.*

At the project start the specification of the asbestos-removal-tasks and technical requirements, initial trials with a robotic mock-up and preliminary simulations will lead to the design and realization of a first version (V1) of the robotic system with a single robotic unit. Using the V1 version of the robotic system, the automated removal of asbestos contamination (operational process) and the according process control system will be developed in several iterations in a testing rehabilitation site (without contamination). During regular workshops, the system will be tested and the central process control system and all subsystems will be advanced by implementing more ambitious functionalities and considering the "lessons learned" and updated requirements. The ongoing developments and updated technical requirements will lead to the design and realization of a second version (V2) of the robotic system with 2 robotic units. The V2 version of the robotic system will be the final prototype used for further developments and the final demonstrations and benchmarking. Using the V2 version of the robotic system, the operational process and the according process control system will be finalized to fulfil all requirements for the robotics use case.

In this report, a precise definition of the technical specifications of the BOTS2REC V1 system is illustrated in order to cover all system development aspects including the BOTS2REC V1 Robotic Unit and V1 User Interface, etc. This task is of great importance as it sets the guidelines what need to be adhered to throughout the project. An architecture and functionality of the system to be developed is provided in detail.

This document is the result of the system specifications and architecture definition phase. However, this is a planning document and therefore the final implementation may not coincide with the architecture described in version 1 of the deliverable Di3.2. Future versions will be released to reflect the up-to-date state of the implemented architecture.

3.1.7 Methods and Work Carried Out

The system specification has been conducted from the collection of partial information of different components provided by the relevant partners involved in its development, and completing it from the point of view of the integrator for a complete and reliable definition of the system.

Starting from conceptual information and/or preliminary, periodically discussion has been organized during this first phase of the project in order to evolve the system V1 concept. This information has been supplemented and detailed based on the progress of discussions and analysis done in between.

Different drafts of the specification have succeeded each until reaching this deliverable describing the system completely.

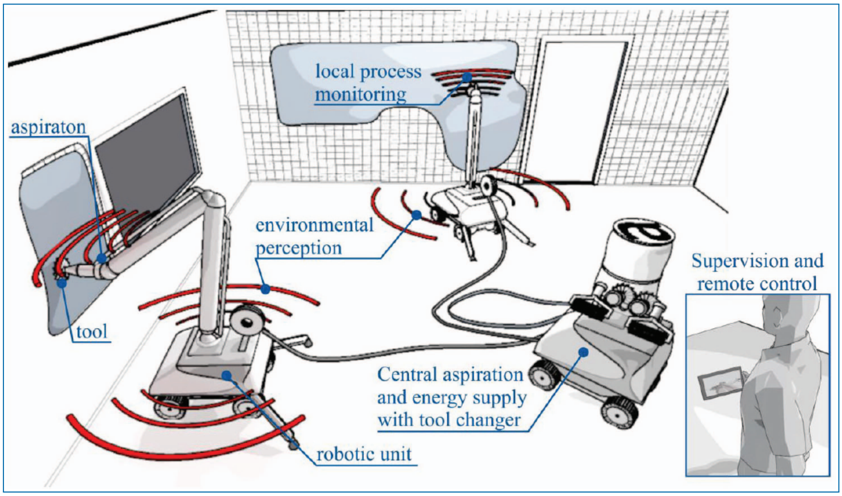


Figure 3.19. Sketch of site with two robotic units during the automated removal of asbestos contamination.

From the point of view of system integration, it has carried out the systematic gathering of information of the elements that forms the V1 system provided by the partners and the information that resulted during different discussions. With this information it has been continuously identified the main open topics to be discussed at subsequent meetings and have been completed those aspects that are part of the whole system and do not apply to a specific component.

In addition, regular discussions have been going on in parallel with the definition of requirements, a fact that has enabled the continuously compliance assessment of these requirements or revise those that could not realistically be met.

3.1.8 Specification of the Technical Requirements for the V1 Prototype – System Specification

3.1.8.1 Introduction: The BOTS2REC System

The proposed robotic system (see Figure 3.19) used for the automated removal of asbestos contamination will consist of multiple mobile robotic units that perform the asbestos-removal-tasks autonomously.

Each unit consists of a mobile platform and robotic arm with different abrasive tool. The combination of optical and radar sensor systems will allow the environmental perception and local monitoring of the asbestos-removal-tasks. Supported by a user interface, the operator can select different areas on a virtual representation of the rehabilitation site and assign asbestos-removal tasks. Based on the user input, the Central process control system plans the task allocation and collaboration between the mobile units and their movements and trajectories autonomously.

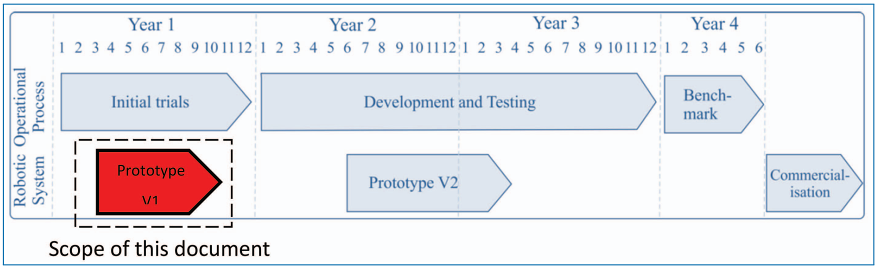


Figure 3.20. Timeline for the overall approach and methodology.

The user interface allows the permanent supervision of the automated process and optional remote control. All robotic units are connected to an aspiration system and energy supply to remove the waste from the rehabilitation site and supply sufficient energy for the robotic units.

3.1.8.1.1 The project phases

Based on the general requirements of the construction and demolition industry and the specific requirements of the robotics use case described above, an operational process and robotic system for the automated removal of asbestos contamination is being developed and implemented in different subsequent phases, as show in Figure 3.20.

At the project start the specification of the asbestos-removal-tasks and technical requirements, initial trials with a robotic mock-up and preliminary simulations will lead to the design and realization of a first version (V1) of the robotic system with a single robotic unit, which specification is the main scope of this document. In general terms, the V1 prototype will be an experimental platform, used by the consortium during regular workshops in a testing rehabilitation site, to test and improve step by step the system and its functionalities forecasted for the project, which will be joined and implemented in the V2 prototype. The ongoing developments and updated technical requirements will lead to the design and realization of a second version (V2) of the robotic system with 1 or 2 robotic units. The V2 version of the robotic system will be the final prototype used for further developments and the final demonstrations and benchmarking, performed under real world conditions.

3.1.9 The Robotic System V1

The focus of the **Robotic System V1** is placed on developing **a single robotic unit**, composed mainly by a mobile platform and a robotic arm. This V1 of the robotic system will not include the central unit, therefore, the support devices (such aspiration) will be included or attached to the single robotic unit.

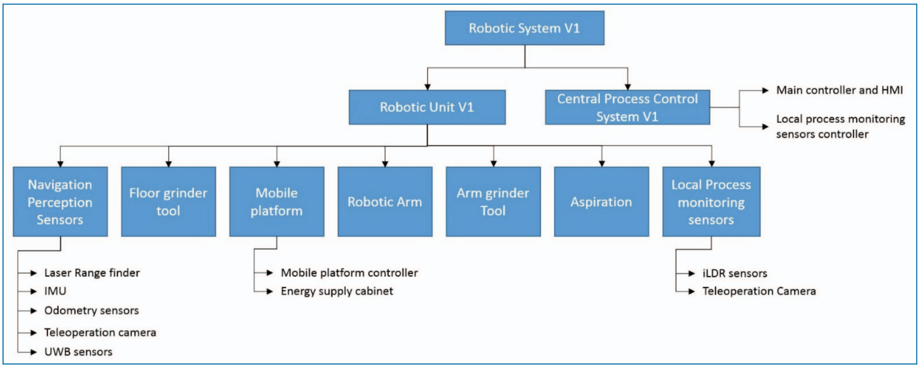


Figure 3.21. General system architecture.

The Figure 3.21 shows the main devices that compose the Robotic System V1:

- 1 Robotic Unit (V1)
- Simplified Central Process Control System

And accordingly, the Robotic Unit V1 will become an experimental platform with all of the components required for the asbestos removal tasks. The main components of this unit are:

- Mobile Platform
- Aspiration
- Supply cable automated reel
- Robotic Arm
- Tool for wall and ceiling grind
- Tool for floor grind
- Process Monitoring Sensors (PMS)
- Navigation and Perception Sensors (NPS)

The detailed Specification of the Robotic Unit and its components is included within this section 3.4 of this document and its related sub-sections.

3.1.10 The Robotized Asbestos Removal Process

3.1.10.1 The robotized procedure

The scenario of the asbestos removal tasks done by human workers allows to understanding how a robotic-system can replace human workers. Considering also that not all tasks the human workers do currently can be automated, for instance the seclusion or the cleaning, three successive periods or phases can be determined in the robotic-system process, as reported in Deliverable *D1.1 Report with a detailed specifications of the asbestos-removal tasks and possible tools* and complemented in the current specification document.

(a) Preparing asbestos removal (done manually, before robotized removal process)

- Identification of asbestos (from D1.1)
- Estimation of the quantities and the spotting (from D1.1)
- Estimation of the dust level (in comparison with test-sites) (from D1.1)
- Adapted seclusion (regarding the estimated dust level and the spotting) (from D1.1)

  Optionally the seclusion will be adapted by adding an additional (soft) layer under the foil in order to reduce the damage of the foil from the robot wheels.
- Installation and test of the ventilation system (suction and smoke test) (from D1.1)
- Robot assembly (platform, arm, aspiration, tools, ...)
- Plug the robot to the external supply generator (placed on the same floor of the worksite)
- The standard operation would be to start creating a map of the flat. This can be done very fast in manual mode. There is no need to autonomously create a map.
- The operator introduces the removal jobs into the system through the HMI interface

(b) Removing asbestos with the robotized system

- The robot starts the removing task autonomously or teleoperated
  - When the bag is full, it is cleaned in the decontamination lock for the waste and put in a cleaned bag that will be put in a big bag with a sign. This operation will be done manually by the operator.
  - If required any tool change or replace any part of it (such disks, etc.), the operator will stop the robot and perform the required action. Then he/she will resume the robotic system operation.
  - If there's a failure of the robotic system, the system will stop and the operator will come to solve the failure. Then he/she will resume the robotic system operation.
- Materials incorporated in hard materials shall not be removed by the designated robotic system: asbestos cement, structural panels, pipes

(c) After asbestos removal (done manually)

- Visual inspection (from D1.1)
- Measurement of the dust level (from D1.1)
- Removal of the seclusion (plastic only used once) (from D1.1)
- Decontamination of the not renewable parts of the robotic unit and removal of renewable gaskets.
- Confinement of the robotic unit into the container solution.

3.1.10.2 Removal process conditions

3.1.10.2.1 Asbestos grinding process parameters

Regarding the removal process parameters, the system specifications collected within this document are based on preliminary inputs. Therefore, the final V1 specifications will be updated after initial trials done with a mockup robotic system (T1.2 and the resulting deliverable *Di1.1 – Technical report with protocols of the trials and specification of the process parameters*) providing information about parameters for a robot guided use of the tools, such normal and lateral forces, optimal process speed, etc.

- The thickness of the product that needs to be removed is between less than a 1mm (for cement rendering for instance) till 2cm (for ceramic tiles for example).
- As required for V1 system, the robot has to be capable of grind walls, ceiling and the floor.
- Taking into account that the same kind of tool will be used for grinding walls/ceiling and the ground, a 80N – 100N normal forces will be considered for the arm grinding tool, as well as for the floor grinding tool.
- About the disc position, the unit will be able to place the tool/disc in different positions against the wall, according to:
    - Disc inclined for rough operation, in firsts steps of grinding process
    - Disc completely parallel to the wall for fine operation, in finishing steps.

3.1.10.2.2 Environmental conditions

Joined to the *D1.1 – Report with a detailed specifications of the asbestos-removal tasks and possible tools* there is a table that shows the different products containing asbestos that this project will cover (Annex "Classification"). This table has been established based on the tool of INRS (Institut National de Recherche et Sécurité / National Institut of Research and Safety), and provides an orientative dust level regarding the material and tool used for the removing task.

In the project, it will be assure the level 2 for the dust maximally:

- Level 1: less than 100 f/l
- Level 2: between 100 f/l and less than 6.000 f/l

The aspiration system of the robotic system (see section 3.4.4) will respect this limit.

On the other hand, in order to keep the level of asbestos particles in the air as low as possible, it might become 's necessary to spray a mixing of water and soap (or surfactant) in order to keep the level of asbestos particles in the air as low as possible in the case that aspiration is not able to maintain the proper levels of dust. In that case, the next specification will be add to taken into . Taking this into account:

- Removal has to be done in the wet environment (from D1.1)
- Robot systems has to withstand water (from D1.1)
- Robotic Unit will needs to have a spraying unit (from D1.1)

Other important aspect regarding the environment where the robot will be operating is the fact that the floor will be covered, in most cases, by a common plastic of a 150 μm of thickness to protect the building ground. This issue has to be also taken into account combined with the wet environment.

3.1.10.2.3 Operation in corridors

According to the requirements stated in Di3.2 part A, the system must be capable of to operate in corridors of the 700mm of width. This fact, together with other restrictions related control and sensors precision entails that the envelope of the robot must not exceed 600mm of width to operate properly.

In order to be able to turn in corridors of that dimensions, a noticeable reduction of the robotic unit dimensions would be needed. This would hinder making that not able to place the placing of all the required components within the allowed space of the platform. Nonetheless, considering that the situation of 2 corridors of 70cm is not frequent, it will be considered corridors of 700mm next to other of 800mm for the design, which are the most frequent (80-90%). Additionally, in small corridors or places with difficulties for autonomous navigations the system will be teleoperated.

Table 1 contains the results of the tests performed in different bent corridors. It is indicated if the platform could turn in the corridors with the complete robotic unit V1 system, or with a simplified robotic unit with less protruding elements. More details are also provided in the deliverable *D2.1 Preliminary simulations of the robotic units*. In the table below there are the conclusion from that study.

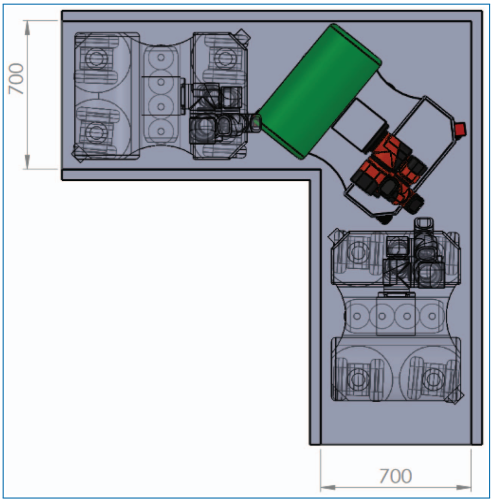


Figure 3.22. Operation in corridors.

Bent corridor Crossing	With robotic unit V1	With simplified robotic unit V1
700x700 corridor	Not able	Able
700x800 corridor	Not able	Able
700x900 corridor	Able	–
800x800	Able	–

3.1.10.2.4 Automated detection of asbestos

For the V1 of the system, the identification of the asbestos contaminated areas will be done manually by visual inspection, as indicated in section 3.3.1.

As well as the initial identification, the verification of the asbestos contamination removal will be done by visual inspection by the operator, and reprogram the system if additional operations are needed.

The automated detection of asbestos by computer vision or other technologies will be analyzed for system V2 even that it is out of the scope of the project.

3.1.10.2.5 Check of disc abrade

It will be done manually, by visual inspection, as done in the manual operation.

3.1.10.2.6 3D scanning of the worksite

For V1, a simplified 3D representation of the worksite will be generated (i.e. by adding the height coordinateds…) after 2D mapping performed by the moving the MP around. On board photogrammetry technologies will be investigated during the V1 testing phase.

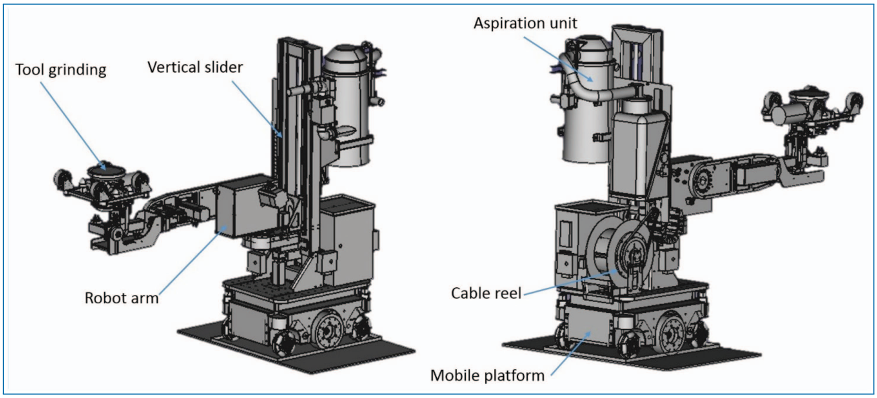


Figure 3.23. Robotic Unit V1 CAD.

For V2 it will be considered to rent a professional 3D vision system. Other technologies, such as on board photogrammetry will be considered in order to simplify and reduce system costs.

3.1.11 Robotic Unit V1 Technical Specification

The overall architecture of the Robotic Unit V1 (RU-V1) is mainly composed of a Mobile Platform (MP), a Robotic Manipulator Arm (RMA) with a single attached Process Tool (PT), including two groups of sensors: Navigation and Perception Sensors (NPS), and Process Monitoring Sensors (PMS). Figure 3.23 shows the main components of the RU-V1. Attached to this document there has been included a table which details the different components and devices that conform the unit V1 and summarizes its main specifications.

The V1 system doesn't consider the use of the Central Supply Unit (CSU) to support the RU-V1. Consequently, in this first version the aspiration unit will be on board of the mobile platform avoiding the need of an automatic pipe reel. Nonetheless, the unit will require an active cable reel for the energy supply and communications, which is described in more detail in section 3.4.8.

As standard procedure to reduce the dust, the environment might be constantly kept wet with a water sprayer. Consequently the robot and ground can be exposed to water constantly. For these reason, the robot will be dustproof and a certain level of waterproof.

3.1.11.1 Mobile Platform

The mobile platform of the robotic units will be based on existing and proven mobile platforms from Robotnik Automation. The platform design will be adapted for the versatile use on the rehabilitation site.

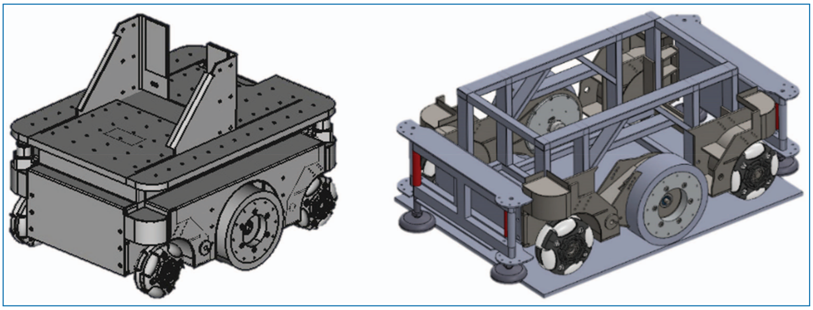
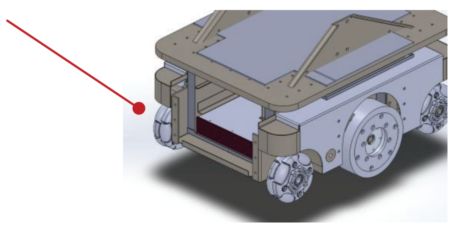


Figure 3.24. Mobile Platform CAD model (left) and tubular structure (right).

The table below includes the mobile platform main specifications:

Type/Model	Robotnik Omnidirectional with 4 wheels swerve drivee
Ground Control software	ROS
Dimensions	Width: 581mm Length: 738mmm Height: 350mm
Weight	95 kg
Payload Weight Capacity	230 Kg
Operational range/altitude	3 m
Safety mechanism	2x Onboard Emergency Stop button 1 x Remote stop 2 x Non-Safety Laser Scanner (There is a protocol that ensures robot is not moving near workers)
Payload Power Capacity	80A/48V(peak) , onboard DC/DC converters will provide different voltages
Power Type	Lithium LiFePO4 batteries 48V 15 Ah 
Autonomy	2 hours using only mobile platform,1, 1 hour using arm. Work is done connected to AC
Charger	input 230VAC; Charging time 1 hour (onboard charger)

Locomotion system	Differential with 2 traction wheels + 4 castors (dual wheel or omniwheel), communication with Control computer using CANOPEN
Maximum speed	1.7 m/s (will be limited)
Minimum turn radius	0, will be able to turn on the spot
Point of contact with the floor	4 omni-wheels in the 4 corners of the footprint, 2 rubber-band wheel in the lateral side
Crossing obstacles capability	Step: 2 cm Ditch: 10 cm
Materials of main parts	Structural parts: Aluminum and Steel Covers: aluminium Wheels: Rubber
Shapes and surfaces geometry	preferably flat or convex to facilitate cleaning
Surfaces processing/finishing	painted or untreated raw
IP protection grade	IP65
Attachment of the arm	The platform will include a vertical slider so the robot arm can be lift to reach a workspace of 3m height. Attachment will be defined using standard ISO screws and mounting flange (attachment between slider and MP will not be ISO flange)

The mobile platform will incorporate different brakes in order to block the platform motion when the emergency stop is triggered. A manual unblocking (brakes off) of the robotic unit must be possible in order to move the robotic unit by pulling/pushing.

3.1.11.1.1 Mobile platform control

The mobile platform controller will be an Intel NUC (Intel i5 processor, 16 GB RAM, SDD disc). More details of the mobile platform control architecture can be found in section 3.4.9 of this document.

3.1.11.1.2 Stabilizers

The first prototype will help to study the tool forces effects in vibration and stability off the platform. Into the mobile platform there will be attachments for passive stabilizers, which will be placed by hand in different configurations to test the results

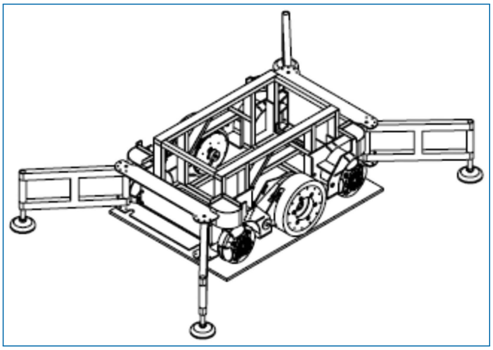


Figure 3.25. Manual stabilizers.

of simulations. After that mechatronic Stabilizers will be designed (if required) for V2 prototype. A support structure to place a stabilizer from the platform to the ceiling will be also forecasted.

In order to provide information to the control system of the presence of this element (i.e. to allow/restirict wider movement that may introduce instability if stabilizers are not present) it will be introduced some limit switch on the stabilizers.

3.1.11.2 Robotic Arm

In order to move the tool to process the different surfaces it will be necessary to place an automated manipulation solution. For the system V1 the manipulation solution will be based on a customized robotic 6DoF arm attached to a Vertical Slider system.

This robotic arm is built with brushless motors with their drivers. Further information for the last update of the robotic arm on Work Package 5 (WP5).

The table below includes the robotic arm main specifications:

robot arm	33 kg
robot shoulder	21 kg
reach	1605mm
payload	18 kg (21 kg with passive compliance)

		Voltage	Nominal power	Nominal speed
Link 1	Base roll	48 V	0,12 kW	3000 rpm
Link 2	SH-pitch	48 V	0,58 kW	3000 rpm
Link 3	EL-pitch	48 V	0,34 kW	3000 rpm
Link 4	w-roll	48 V	0,17 kW	3000 rpm
Link 5	w-pitch	48 V	0,17 kW	3000 rpm
Link 6	w-yaw	48 V	0,17 kW	3000 rpm

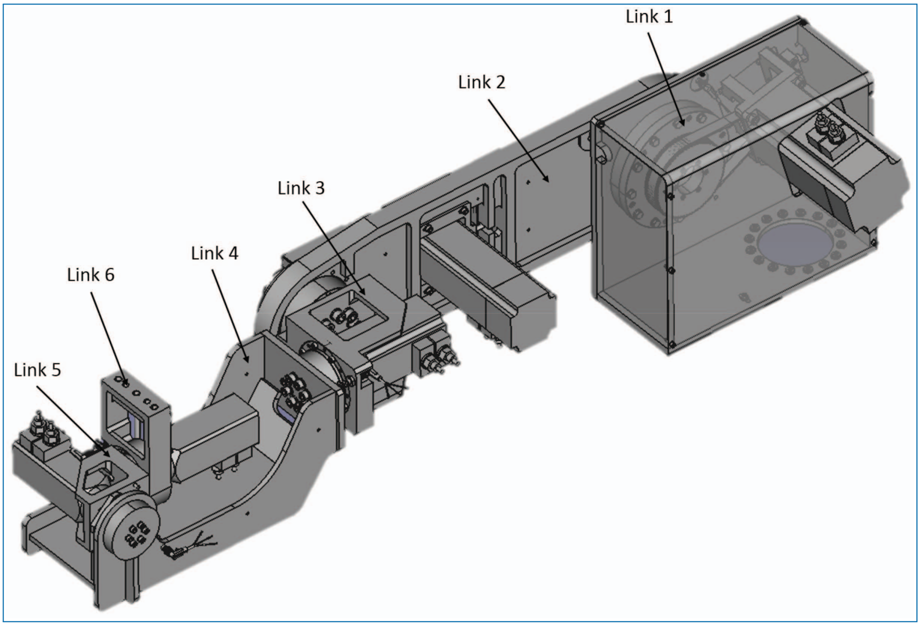


Figure 3.26. Robotic Arm Model.

Figure 3.27. Robotic Arm Controller.

3.1.11.2.1 Robotic arm Control

The robotic arm control will be based on a distributed process based on 2 different CPU:

- A Beckhoff CPU CX9020 with 10 I/O attached cards will be the low level controller part for the robotic arm.
- An Intel NUC "PC" to perform the high level control: path planning, task management, etc.

Processor	ARM Cortex^{TM}-A8, 1 GHz
Flash memory	256 MB MicroSD (optional expandable), 2 x microSD card slot
Internal main memory	1 GB DDR3 RAM
Persistent memory	128 kB NOVRAM integrated
UPS	1-second-UPS integrated (optional)
Interfaces	2 x RJ 45 (Ethernet, internal Switch), 10/100 Mbit/s, DVI-D, 4 x USB 2.0, 2 x optional interface
Diagnostics LED	1 x power, 1 x TC status, 2 X bus status, 2 x flash access
Clock	Internal clock with battery backup for time and date (battery replaceable)
Operating system	Microsoft Windows Embedded Compact 7
Control software	TwinCAT 2 PLC runtime or TwinCAT 2 PLC NC PTP runtime
Power supply	24 V DC (-15%/+20%)
Current supply	I/O terminals 2 A
Max. Power loss	5 W (including system interfaces)
Dielectric strength	500 V_eff (supply/internal electronics)
Dimensions (W x H x D)	84 mm x 99 mm x 91 mm
Weight	approx. 590 g
Operating/storage temperature	-25 °C ... +60 °C / -40 °C ... +85 °C
Relative humidity	95 % no condensation
Vibration/shock resistant	Conforms to EN 60068-2-6 / EN 60068-2-27/29
EMC immunity/emission	Conforms to EN 61000-6-2 / EN 61000-6-4
Protection class	IP 20

3.1.11.2.2 Vertical Slider

In order to place the industrial arm in different height positions, an automated vertical slider will be implemented and adapted to be attached to the mobile platform and able to be controlled trough the robot control I/O.

weight	73 kg (including robot yaw motor)
dimensions	1440x300x86
stroke	890 mm
Supply voltage	48 V
Power	0,150 kW
Nominal speed	2000 rpm

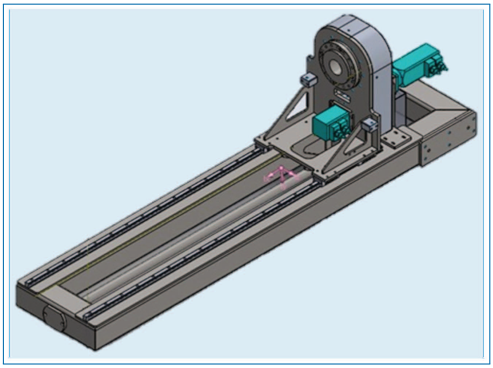


Figure 3.28. Vertical slider.

The slider will have the enough height in order to allow the robotic unit reach the ceiling height requirement at the same time to be able to meet the height limitation of the robotic unit.

3.1.11.3 Tools

The V1 robotic unit will be equipped with 1 tool, to be placed in different locations, in order to perform the required asbestos removal task for this previous version. Taking into account that the V1 system will be used as a test platform for further developments, it has been only required as mandatory that the unit will grind walls, ground and ceiling of the asbestos site, leaving the removal of tiles and other materials for being dealt in V2 prototype. Therefore, the V1 unit will be equipped the following:

- grinding tool attached to the arm's end effector, for grinding walls, ceiling and floor (see 4.3.1)
- it will study how to attach a grinding tool to the lower part of the mobile platform, for grinding the floor (see 4.3.2)

Using these tools, as checked in D1.1 the maximal dust level will be inside the **level 2: between 100 f/l and less than 6.000 f/l**.

Even the tool exchange is no predicted, any tool exchange to be performed in the V1 system will be done manually by the operator. Therefore, no active tool changer units will be implemented on this prototype version.

As indicated in section 3.3.2.5, the disk abrading will be performed by visual inspection to be carried out by the operator as done in the manual process.

The tool to be attached at the arm end effector will be a manual grinder tool adapted for being held and operated by the robot. This tool will be used to grind walls and ceiling and will be linked to the vacuum aspiration system described in section 3.4.4.

The necessary supporting structure will be developed and any required modification to the original tool will be performed. On the adaption of the tool will be taking into account the aspiration head and its pipe.

Figure 3.29. Manual grinder tool to be adapted to the Robotic Arm.

The tool is available and will be tested in two sizes. The main specifications of the tool will be similar to the ones in the tables below, corresponding to the manual tools:

Type/model	BLASTRAC BGV-180AV
Power	2600 Watts (performance 97%)
Supply Voltage	230 Vac – 50Hz – (2P+T)
Rotation Speed	6600 rpm
Weight	5,46kg (without cord)
Disc diameter	Ø180 mm
Dimensions	495mm / 185 mm / 325mm
IP protection	n/a
Acoustic pressure:	n/a

Type/model	BLASTRAC BGV-125AV
Power	1,3 kW
Supply Voltage	230 Vac – 50Hz – (2P+T)
Rotation Speed	11000 rpm
Weight	3,2kg (without cord)
Disc diameter	Ø125 mm
Dimensions	495mm/185 mm/325mm
IP protection	n/a
Acoustic pressure:	n/a

This tool will be adapted and sealed in order to reach the operation and environmental conditions required for this V1 unit. A force/torque sensor will be attached at the end effector of the robot arm, although there is the option to have a passive compliance actuator.

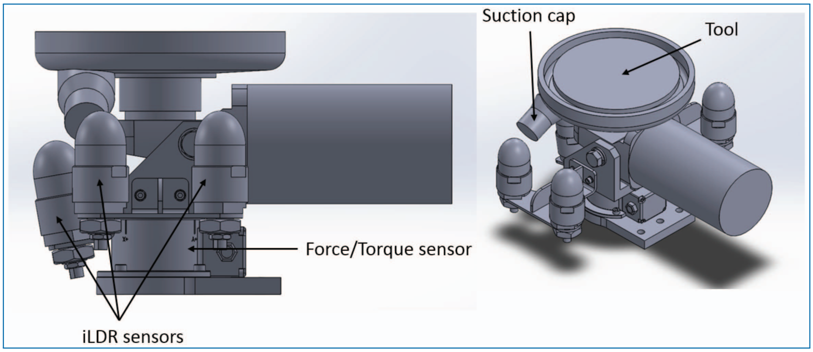


Figure 3.30. Sketch of the adaption of manual grinder tool to the Robotic Arm.

The tool will be controlled through the I/O cards of the arm controller placed on the Robot Arm Cabinet B1, and with the help of auxiliary relays and other protection devices to be placed on the Robot Arm Cabinet B2 described in section 3.4.7.

For grinding the floor, the same tool will be able to be attached directly to the mobile platform in order to perform some tests. The platform will include any required automated mechanism for its proper operation during locomotion of the platform and its normal operation.

3.1.11.4 Waste/Dust Aspiration

Taking into account the minimum aspiration pipe diameter, around Ø35mm, the RU-V1 will include an aspiration placed on the mobile platform in order to avoid the difficult of managing this kind of pipes and the need for an active pipe reel of high dimensions.

This will suppose that the mobile platform should carry with the aspiration system additional load. In addition, the aspiration system must be as compact as possible taking into account the reduced space available in the mobile platform and the whole robotic unit. The consequence of this is that the aspiration system must be splitted in half for a better assembly and save more space.

As will be done with the different tools, the aspiration system will be based on a commercial aspiration device which will be adapted to be integrated on the mobile platform.

The main specifications of this aspiration/ dust collector will be similar to the one in the table below, which corresponds to the commercial device:

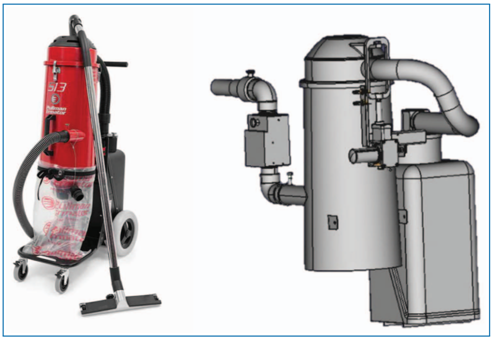


Figure 3.31. Aspiration system device S13 from BLASTRAC, parts of the CAD model.

Type/model	S13
Dimensions (W/L)	680x380x1200 mm
Weight	27 kg
Power	1200 W
Supply Voltage	230Vac single phase (50Hz)
Cleaning	Manual impulse
Bag capacity	15 l
Aspiration	210 m3/h
Pressure	22 kPa
Main filter	99,5 % (1,5 m2)

The aspiration system will be controlled through the I/O cards of the arm controller, with the help of auxiliary relays and other protection devices to be placed on the robot arm cabinet B2 (see section 3.4.7). This system will include almost an input to switch on/off the system and an output for alarm (i.e. bag full, filter blocked …)

3.1.11.5 Decontamination, containment and transportation

It must be taken into account that the V1 prototype will not operate in real contaminated worksites. Therefore, the decontamination and containment measures are introduced in this V1 for testing purposes.

3.1.11.5.1 Decontamination and containment

As mentioned in the previous section, the robotic unit won't work in contaminated areas so there will be not decontamination process, just cleaning process.

The actual current decontamination procedure de-contamination requires 2 different protection actions for contaminated devices. The devices use are protected with a gasket for operating inside the contaminated area which is removed before the the second protection action, cleaning the device in a shower.

Regarding the RU-V1, in real contaminated worksites, it will use the following protection measures:

- The arm and the vertical slider will be covered by a renewable gasket, as done in most of dangerous nuclear operations, for instance.
- Regarding the Mobile Platform, it will be specially prepared and sealed in order to be directly washable.
- All external sensors will be prepared and sealed in order to be washable directly.
- The tool will be sealed and/or able to withstand operating and decontamination shower conditions.

3.1.11.5.2 Transportation

As pointed out the beginning of this section, the V1 unit will not operate in real asbestos contaminated sites. On this basis, it can be asserted that no special confinement or containment conditions must be considered for this V1 prototype. Nevertheless, the necessary protection measures against asbestos contamination will be considered and implemented in V2 prototype.

The necessary measures to ensure the safety and proper transportation of the V1 unit and all of its components from development and integration sites to testing sites (and viceversa), such protection boxes, pallets, etc., will be analyzed and put into practice.

3.1.11.6 Energy supply

The power supply of the robot will be 230Vac (P+N+T). It will be connected to an external power supply placed outside the contaminated area (i.e.: a diesel generator) in order to get the enough power which cannot be extracted from the building main supply. This external power supply must provide 230Vac single phase for V1 and 400Vac tri-phase for V2, and a power over 10kW.

The connection between the RU-V1 and the external power supply will be done by and extended cable through the cable reel solution described in section 3.4.8.

In the attached document *PowerSupply-Layout_v1.pdf* there's a list of the different consumer devices and all ac-dc/dc-dc converters of the design. The mobile platform will include different ac-dc converters for supplying its integrated components such the mobile platform controllers, the IMU sensors, the laser sensors, etc.

More details are also provided in the deliverable *Di3.1 Specification of the system architecture and interfaces*.

The power required by the different RU-V1 elements are described in the attached document: *Equipment List*.

It must be taken into account that a simultaneous operation of all devices is an improbable situation. Therefore, to determine the main supply cable section it will be considered the scenarios described below:

Scenario	Description	Power	Calculated cable section
A	Mobile Platform (1kW) + Tool Grinder (1,62,6kW) + Aspiration (1,3kW2kW) + battery charger (1,6 kW) + Sensors and Others (10,5 kW)	5,96,4 kW	4 mm^2 heating 4 mm^2 voltage drop (4,93,0%) for a 25m cable
B	Arm (21,7kW*) + Tool Grinder (1,62,6kW) + Aspiration (1,23kW) battery charger (1,6 kW) + Sensors and Others (10,5kW)	6,6 kW	4 mm^2 heating 4 mm^2 voltage drop (5,6%) for a 25m cable

*Considering nominal power of each arm motor. A factor of simultaneity must be applied for a more approximate calculation.

A scheme of the power supply is provided in the attached document: *PowerSupply-Layout_v10.4.pdf*

3.1.11.7 Electric Cabinets

The robotic Unit will include different electric cabinets where all the electric and electronic devices will be located in. The cabinets on the unit will be:

- Mobile platform cabinet A1, located inside the MP, it includes all the MP control and power supply elements, and the rest of control devices: router, NUC controllers, etc.
- Mobile platform cabinet A2, located on the exterior part of the Robotic Unit, will allocate theiRPU and the signal conditioning of the force/torque sensor.
- Robot arm cabinet B1, located inside the MP, will allocate the Beckhoff controller, the DC/DC converter, and the safety auxiliary relay board.
- Robot arm cabinet B2, located on the exterior part of the Robotic Unit, behind the vertical slider, will allocate the arm motor drivers, the DC/DC converter and the safety relay board.
- Battery charger box, located on the exterior part of the Robotic Unit.

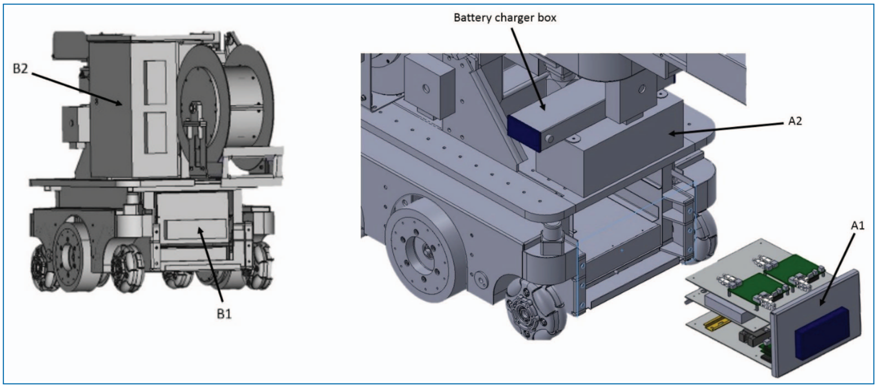


Figure 3.32. Cabinets.

3.1.11.8 Cable reel

To manage the length of the cables, it will be necessary install motorized reel, similar as the one shown in Figure 3.33.

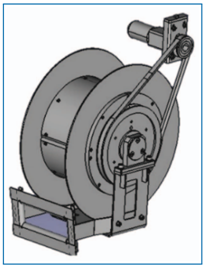


Figure 3.33. Motorized reel custom by TLABS.

This cable reel will incorporate an active control based on the odometry of the mobile platform. The main specifications of this device are listed in the table below:

Type/model	Custom by TLABS
Dimensions	Ø400mm x 150mm (only collector drum)
Cable capacity	25m 1 x (3G 4mm2 + 6x1mm2)
Weight	14.5 kg. (aprox., without cable)
Power	57,6 W (max torque)
Nominal current	2,4 mA (max torque)
Supply Voltage	24 V
speed	64 rpm (no load), 45 rpm (at max. torque)
Finished surface	Polyurethane painting resistant in corrosive environments
IP protection	IP-65

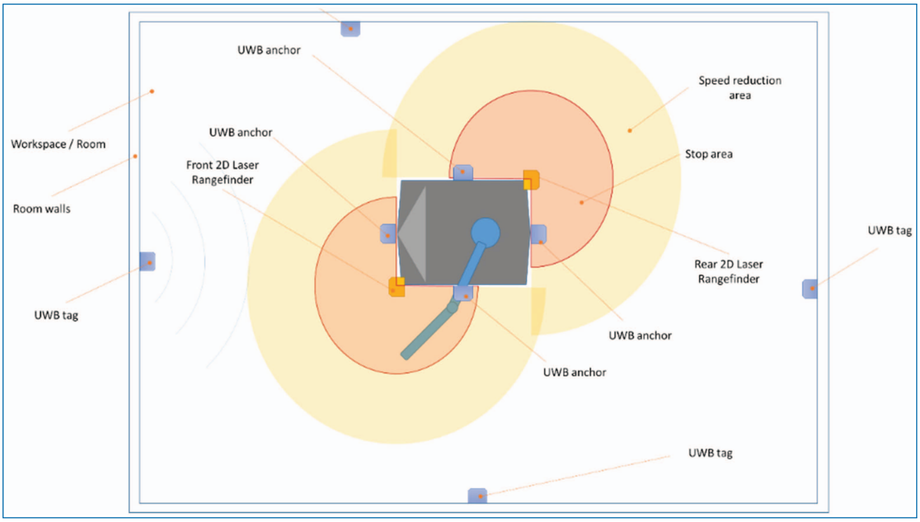


Figure 3.34. General overview of environmental perception sensors.

3.1.11.9 Navigation and Environmental perception sensors set

A set of sensors for perceiving the environment and positioning the robotic unit will be placed on the robotic system. With this purpose, for the environmental perception and navigation, the V1 system will include:

Sensor	Purpose
1 x UWB System, e.g. 4 anchors on the platform and min. 4 tags in the room	Localization
2 x Camera	Backup in case navigation fails or teleoperation mode
2 x LIDAR (in opposite corners of platform)	Localization/Mapping
1 x IMU	Localization
1 x Odometry	Localization
1 x Infrared	Collision avoidance

In Figure 3.34 General overview of is possible to see a sketch with the location of the above mentioned sensors.

3.1.11.9.1 Laser Scan sensors

As described in Figure 3.34: General overview of 7, 2 Laser scan sensors of 270° coverage will be placed on 2 opposite corners of the platforms in order to cover the whole area around the robotic unit. This laser scan sensors will be used with the following purposes:

(a) to avoid collisions with objects or other robotic units
(b) to build a map and recognize the robotic unit position (SLAM or similar), mainly for navigation.

Taking into account that the MP displacements are displacements are omnidirectional, the location is in two opposite corners so the 4 sides of the robot are covered.

Figure 3.35. Location of Laser scan when it is used for safety and Hokuyo UST-10LX laser scan sensors.

The laser scan sensor mounted on the mobile platform will be a Hokuyo UST-10LX (see Figure 3.35) or similar. Its main specifications are:

Supply voltage	12VDC/24VDC (operation range 10 to 30V ripple within 10%)
Supply current	150mA or less (during start up 450mA is necessary.)
Light source	Laser semiconductor (905nm) Laser class 1 (IEC60825-1:2007)
Accuracy	±40mm
Repeated accuracy	$\sigma < 30$mm
Scan angle	270°
Angular resolution	0.25°
Start-up time	Within 10 sec (start-up time differs if malfunction is detected during start up)
Input	IP reset input, photo-coupler input (current 4mA at ON)
Output	Synchronous Output, photo coupler open collector output 30VDC 50mA MAX.
Interface	Ethernet 100BASE-TX
LED display	Power supply LED display (Blue): Blinks during start up and malfunction state.

Ambient temperature	−10°C to +50°C
Ambient Humidity	Below 85%RH (without dew, frost)
Storage temperature	−30°C to +70°C
Storage Humidity	Below 85%RH (without dew, frost)
Shock resistance	196m/s2 (20G) X, Y and Z direction 10 times.
Protective Structure	IP65
Material Front case	Polycarbonate, Rear case: Aluminium
Surrounding intensity	Less than 15,000lx
ROS Driver to acquire laser data	SLAM algorithms available
Detection range	0.06m to 10m (white Kent sheet) 0.06m to 4m (diffuse reflectance 10%) Max. detection distance : 30m

3.1.11.9.2 IMU

The IMU mounted on the mobile platform will be an L3GD20H chip, integrated on Pixhawk controller. Its main specification are:

Supply voltage	2.2V to 3.6V
Supply current	5mA
Operating temperature range	-40°C to +85°C
Value output data	16 bits
Temperature output data	8 bits
Interface	I2C/SPI
Measurement range	±245, ±500, ±200 dps (user selectable)
Sensitivity	8.75, 17.50, 70.00 mdps/digit (user selectable)

Pixhawk specifications:

Processor	32-bit ARM Cortex M4 core with FPU 168 Mhz/265 KB RAM/2 MB Flash 32-bit failsafe co-processor
sensors	MPU6000 as main accel and gyro ST Micro 16-bit gyroscope ST Micro 14-bit accelerometer/compass (magnetometer) MEAS barometer

Power	Idela diode controller with automatic failover Servo rail high-power (7 V) and high-current ready All peripheral outputs over-current protected, all inputs ESD protected
Interfaces	5x UART serial ports, 1 hig-power capable, 2 with HW flow control Spektrum DSM/DSM2/DSM-X Satellite input Futaba S.BUS input PPM sum signal RSSI (PWM or voltage) input I2C, SPI, 2x CAN, USB 3.3V and 6.6 ADC inputs
Dimensions (WxHxL)	50 x 15.5 x 81.5 mm
Weight	38g

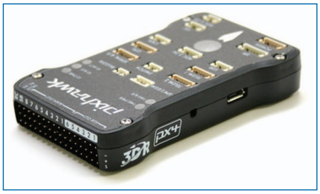


Figure 3.36. Pixhawk controller.

3.1.11.9.3 Encoders

Odometry requires a method for accurately counting the rotation of the robot wheels. A standard method for doing this is to instrument the wheels with encoders. The Mobile platform includes encoder 15T Thru-Bore eEncoders. Its main specification are:

Input voltage	5Vcc fixed voltage for communication 4.75 to 24 Vcc max for temperature up to 85°C 4.75 to 24 Vcc for temperatures between 85°C to 100°C
Input current	100 mA max (65 mA typical) with no output load
Output format	Incremental

Output types	– Open collector – 20 mA max per channel – Push-Pull – 20 mA max per channel – Pull-Up – open collector with 2.2K? – Pull-Up 20 mA max per channel – Line Driver – 20 mA max per channel (meets RS 422 at 5 Vcc supply)
Marker(index)	Once per revolution. 190 to 10000 PPR: gated output A 1 to 189 PPR: Ungated
Max. frequency	Standard frequency response is 200 kHz for PPR 1 to 2540 500 kHz for PPR 2541 to 50000 1 MHz for PPR 50001 to 10000
Noise immunity	Tested to BS EN61000-6-2; BS EN50081-2; BS EN61000-4-2; BS EN61000-4-3; BS EN61000-4-6; BS EN500811
Max shaft speed	8000 rpm
Bore size	8mm
Weight	100g
Operating temperature	−20° to +85° C standard models −40° to +85° C for low temperature option −20° to +100° C for high temperature option −20° to +120° C for extreme temperature option
Storage temperature	−25° to +85° C
Humidity	98% RH non-condensing
Vibration	10 g @ 58 to 500 Hz
Shock	10 g @ 11 ms duration
Sealing	IP50 standard; IP64 available

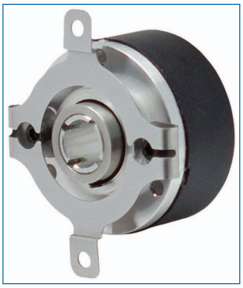


Figure 3.37. Encoder used in the mobile platform.

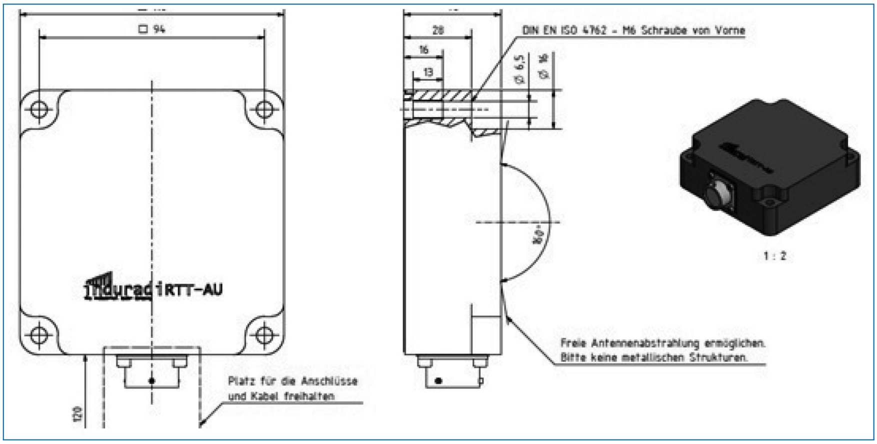


Figure 3.38. UWB anchor design.

3.1.11.9.4 UWB positioning sensors

The UWB sensor provides the robotic unit position based on different measures between the anchors placed in the mobile platform and the tags placed on the walls of the different rooms. Therefore, 4 or 5 devices (anchors) of the UWB positioning system will be placed on the different sides of the robotic unit, as depicted in Figure 16. If required, more devices will be added to the robotic unit in order to ensure the proper operation of the system and getting the required positioning accuracy.

The Two technology can be implemented is based on : ToF (Time of Flight) based measurements even or TDoF (Time Difference of Flight) measurements can be considered if necessary.

This positioning system will require also to place different emitter tags inside the room, also depicted in Figure 3.38. It will be required almost at least 4 emitter tags per room, even there is no upper limit of nodes.

In the table below there is a summary of the main characteristics of this sensor system (T=tag, A=anchor):

Weight (kg)	T,A: ~0.3kg
Voltage Range	T: Battery 8 V, A: 65 V
Power consumption	T,A: ~1W
Rechargeable battery	7V to 60V, 1200mAh
Data types/ formats	output will be platform pose data format not yet defined
Hardware interface	CAN
Communication speed	110kBit/s to 6Mbit/s

Frequency range	6 to 7 GHz
Connector	8 pin Souriau (M12)
Update rate	~10Hz
Resolution	mm
Accuracy	>=5cm
Measurement range	~200m
On-board pre-processing features	Pose calculation
Anchor size	80x75x56mm

3.1.11.9.5 Teleoperation Cameras

In order to perform the more complex removal jobs, the robotic unit V1 will incorporate 2 RGB cameras to help on the remote teleoperation from the Simplified Central Process Control System and HMI in the outside of the contaminated area.

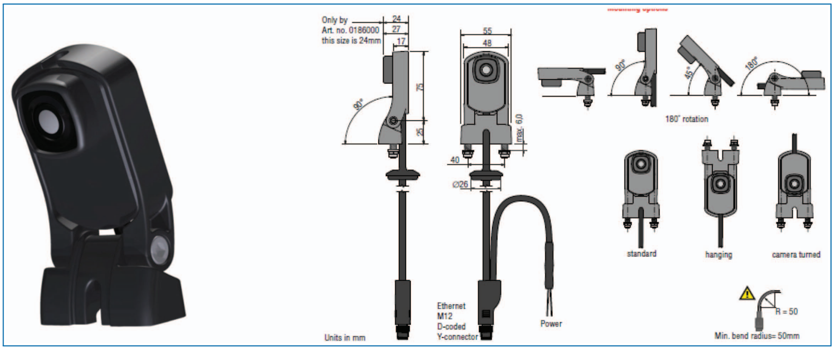


Figure 3.39. Teleoperation Cameras – ORLACO Camera EMOS.

The system will include 2 Ethernet cameras ORLACO Camera EMOS with the following specifications:

Sensor element	High resolution 1/3" CMOS rolling shutter, 1280H x 960V
Field of View	120° version
Video	image 60fps at 720p SDR, 45fps at 960p SDR image processing and 56fps at 720p HDR, 43fps at 960p HDR image processing
Protocols	RTP (MJPEG RFC2435 and h.264 RFC6184) over UDP, PTP and gPTP, ISO17215-2014, IEEE1722 (AVB)

IP address	DHCPv4 or static IPv4 (IPv6 possible)
Latency	<100ms depending on hardware processing platform (50ms demonstrated on Orlaco hardware)
Light sensitivity responsitivity	5,5V/lux-sec, Low light feature (<0,1Lux)
High dynamic range	>115dB
Compression	MJPEG (H.264 expected in Q1, 2016)
Interface	100Mb/s (Fast Ethernet)
Image processing	Color and gamma correction, 3D noise correction, edge enhancement, digital WDR, advanced contrast enhancement, auto white-balance, auto exposure control, mirroring, flipping, photometric and geometric lens distortion correction
Power input	12/24V/DC. Below 7V: camera is non-functional. Above 33V the overvoltage protection is activated. This overvoltage-protection is deactivated below 30V. Powercircuit is protected up to 80V/DC. Outputs are Short Circuit Protected.
Power consumption	<2W
Connector	Cable 6 wire: 2x twisted pair for data and 2 wires for power supply. Connector 4-pin M12 d-coded for data and open wires for power supply.
Housing	Anodised aluminium, black, UV resistant, light fastness >8, corrosion proof according IEC 60068-2-52 salt mist, cyclic.
Ingress protection	IP68 according to IEC 60529 (up to 10 m under water), IP69k according to DIN 40050-9
pressure cleaning/washing	with water: 14-16L/min. 80°C and 100 bars flow
Lens glass	Chemically hardened, toughed, tempered float glass: 5 to 7 times stronger than ordinary glass, protected against acid: class 2-3; DIN 12116, passed flying stone test
Shock constancy	Shock and vibration resistant for usage on trucks, cranes, fork-lifts, maritime applications, machinery

Camera bracket Material	glass reinforced plastics, test: 50 Nm at -40°C to +85°C
Weight	0,24kg. including cable, bracket and mounting material. 0,30kg. in standard packing
Operating temperature	-40°C to +85°C
Storage temperature	-40°C to +125°C

The cameras will be placed on each side of the slider-arm structure. With the cameras in this position an operator will be able to see most of the surrounding area of the robotic unit.

In order to avoid dust problems, it has been considered a dustproof and waterproof camera (IP68) to work in contaminated environments as mentioned in previous sections. Cleaning will be done manually.

3.1.11.10 Local process monitoring and teleoperation sensors set

A set of sensors for local process monitoring and teleoperation will be placed on the arm end effector. With this purpose, the V1 system will include:

- **iLDR sensors** for measuring the removal process

3.1.11.10.1 iLDR sensors

For local process monitoring it will be developed a sensor system consisting of 4 5 iLDR sensors (120 GHz frequency), for 1D distance measurement in one direction are will be developed. This technology is especially robust under dusty environmental conditions which will fit the prototype requirements.

This iLDR sensors will be located as described in Figure 3.40. This configuration will maximize the grinder disk reach and at the same time will allow to:

- Monitor the processed material depth
- Get the Tool orientation referenced to the wall in real time

Data processing will be done by a computer installed within the Control CabinetA1 (see section 3.4.7)

Data transfer from the tool to the computer will be done by USB2.0 cables through and USB-Hub which will be used for supplying the sensors with 5Vdc. The accuracy will depend on the number of targets found. Single targets (single peak) can be found more accurately. This sensors are not affected for the process vibration

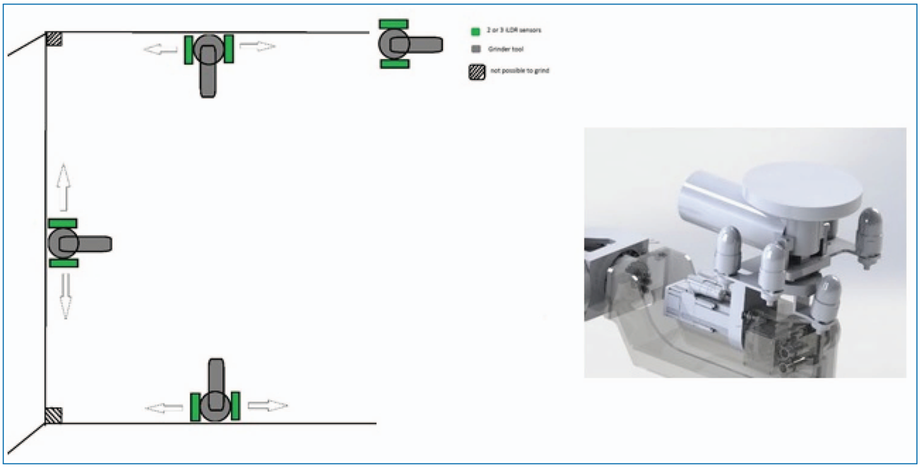


Figure 3.40. iLDR Sensors Configuration (left) CAD model iLDR sensors (right).

due to the incorporated IMU sensors. In the table below there is a summary of the main characteristics of this sensor system:

Frequency	119GHz to 126GHz
Max. radiation power	0dBm (1mW)
Operation principle	FMCW (Frequency modulated continuous wave)
Lens diameter	45mm
Lens length	about 35mm
Lens material	PTFE
Power supply	5V/2.5W – a high power USB connection can be used; optional nominal 24V (7V....65V), Power over Ethernet (802.3af/at)
Interface	USB, optional Ethernet 100BASE-TX, IEEE 802.3 Clause 25 with increased power requirements
Output data	Raw data IQ-sampled
Measurement rate	up to 1000
Single measurement duration	about 220μs
IP protection	IP67 or better probably IP69/K
Temperature range	−40...+85°C
Dimensions	60x60x60mm
Weight	350 gr

3.1.11.11 Emergency stop and safety during operation

For the system V1 preliminary prototype the machine safety area will be outlined with the red ribbon and near the laptop used for system validation there will be an electrical box with emergency button and system reset button. Similar devices are depicted in Figure 3.41.

Figure 3.41. Work area safety measures.

Other emergency stop devices will be installed in the robotic unit, in a visible an easy accessible location. Once the emergency stop is triggered, mobile platform and arm brakes will be triggered in order to ensure a fail-safe behavior of the system. Also, it is also planned to could be use an emergency barrier stop, placed outside of the contaminated area, this signal will also be able to stop the operation of the robotic unit. Below a figure of the test site with the safety elements is shown.

More details can be found in Di3.3

3.1.11.12 Communications and Control Architecture

In order to the operator will be able to send asbestos-removal-tasks or receive some feedback about the work of the robot, it is necessary create a communication network.

A Wi-Fi router will be installed on the robot to establish communication with the operator from a not contaminated area.

All the controllers of the robot (arm controller, mobile platform controller, UWB controller, iLDR controller) will be connected to the router Wi-Fi via Ethernet cable. Below, is detailed with the way to connect each senor or actuator to its own controller.

3.1.11.12.1 CPCS

Taking into account that the V1 system is set for research and testing purposes in the earlier phases of the system development, a simple version of the Central Process Control System (sCPCS) will be developed just with essential functions.

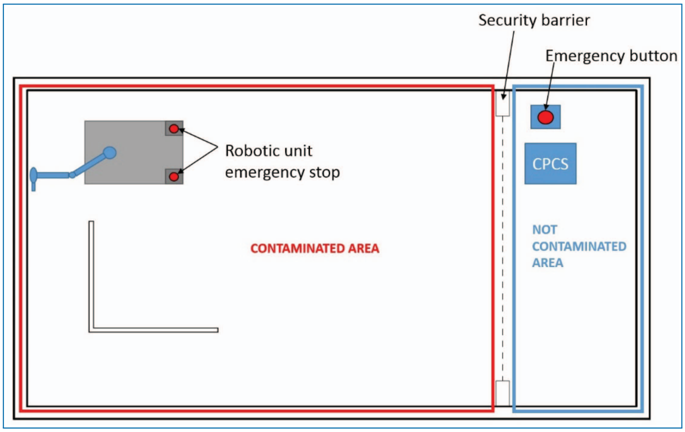


Figure 3.42. Test site with safety elements.

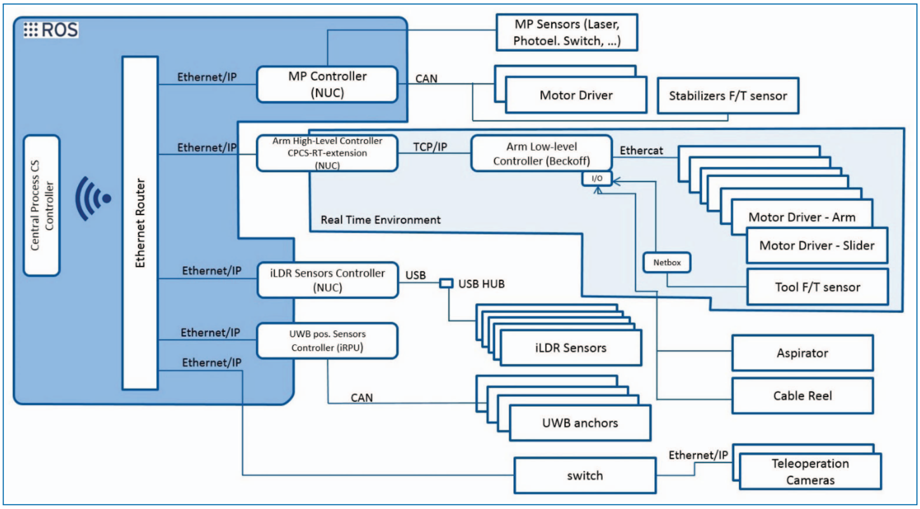


Figure 3.43. Control architecture.

As pointed in section, the CPCS will be further developed during the regular tests and modifications to achieve its final version for system V2.

The essential functions that the CPCS must have for V1 are:

- Teleoperation through a computer screen and a standard keyboard
- Automated execution of simple grinding tasks with simple geometries (such square areas).
- Monitoring of process parameters
- Alarms and warning management

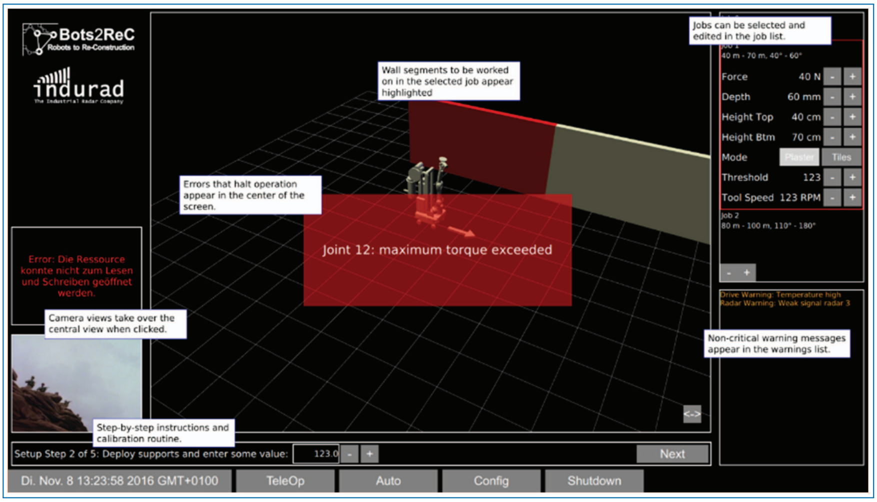


Figure 3.44. Preliminary HMI (running on laptop and desktop PC).

The CPCS will be set in a portable computer to be placed next to the robotic unit or outside of the working area, depending on the tests being carried out.

The computer which will host the control system (CPCS) will be able to operate in soft real-time. The main control loops (kinematics, start/stop signals, alarms, etc.) will be executed on Beckhoff controller and on a TLABS NUC with RT-Preempt for real-time.

3.1.11.12.2 HMI interface

The HMI will be set in the same screen as the controller, both in the same laptop or desk PC. It will be developed and implemented a multifunction HMI interfaces between the autonomous system and the operator. The HMI will control each operation of the different phases of the complete process from the initial operator task programming.

It will be adapted to be introducing the asbestos removal jobs location, based on a previous 2D/3D map and its parameters.

It must have the controls for planning and supervision of the platform motions in each process and security parameters: free supervised motion for general displacements of the platform, planned motion for getting navigating inside the worksite and planned motion for grinding process.

The operator must be able to supervise the removal process, and teleoperate the system through different live images coming from the cameras placed on the platform, modify the control strategies and parameters, and plan actions of the robot, between others. Also the operator must be able to supervise the removal jobs process and read in real-time the process variables.

The HMI will include safety parameters and alarms that show the detection of danger situations like a worker detected into the danger zone by the perception system, collisions or occlusions of the computer vision systems and problems on the platform or its components.

3.1.12 Outlook and Future Work to be Carried Out

The definition of the main technical specification of the V1 system and the devices that compose it has been done, according to the Work Program. With this work, it has updated the detailed information of each part of the system according to the design phase works.

A sufficient level of detail has been provided in order to get a detailed description of the robotic unit V1. Thanks to the information collected and from the tests to be performed, it will help for define and design the robotic unit V2.

3.1.13 Summary and Conclusion

In this deliverable the technical specifications for Robotic Unit V1 has been defined, which will become the basis for the further references in the becoming phases of the project.

It is therefore concluded that aim of the definition of system technical specification has been achieved and the work has been carried out according to the work program.

Deliverable Di4.1
3D CAD drawings, manufacturing drawings and list of part for V1

Authors: Miguel Moreno, Tim Detert

3.1.14 Deliverable in the Context of the Work Program

This internal deliverable is an output from *Task 4.1 "Design-adaption of the mobile platform"* to show the Design of the first prototype (V1) of the Bots2Rec platform.

It uses the input from previous deliverables "*Di3.1 Specification of the system architecture and interfaces*" and "*Di3.2 Specification of the technical requirements for the V1 prototype*".

This deliverable contains the CAD files, CAD drawings, part lists and electrical drawings necessary to manufacture the first version of the mobile platform, as a part of Milestone 1 (Overall system layout and design of the first prototype and central system finished) Following to this document is the manufacture of the Mobile platform, its test, and integration with the rest of subsystems included in First prototype.

3.1.15 Methods and Work Carried Out

To reach this deliverable the platform has been dimensioned according to the basic requirements specified in task 3.1, 3.2 and 7.1.

3.1.15.1 Kinematic configuration

Different kinematic configurations have been evaluated, including different suspension system. The main requirements considered for design of the mobile platform were: (See Di3.2 for further details)

- High mobility to be capable of moving through corridors and turning 360 degrees in place
- Reduced footprint to pass through doorway and to fit inside an elevator.
- Stability to carry high Centre of Mass and a total weight of the robot of 300Kg.
- Capability of crossing small obstacles in manual operation
- Preservation of the protection of the room (plastic sheet)

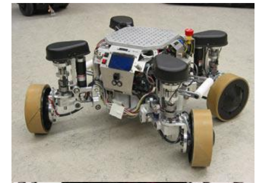
The configurations preferred to meet the requirements are "Swerve Wheels", "Dual Swerve Wheels" and "Differential Drive". The next table shows them.

Another question considered for the kinematic configuration is that the surface over the platform is moving could be a plastic covering the floor, the platform needs to move over this surface without damaging it. So tests over this surface have been done with different wheels to see the damage created.

The cover material used for testing is Polyethylene film with a thickness of 37 and 125 microns (the thicker is the one recommended by Bouygues Construction). The wheeled vehicles used are Robotnik existing platforms:

- **Robotnik AGVS robot.** 2 Swerve wheels + 2 fixed wheels. Robot weight 250 Kg.

Table 3.1. Kinematic configurations

Configuration	Advantages	Drawbacks	Picture
A) Swerve Wheels. 4 directional wheel on each corner.	• High maneuverability: can move in any direction without rotating the platform • More traction due to 4 motorized wheels.	• High complexity because of the quantity of motors/servodrives. • Higher weight • To change direction of robot movement the wheel often has to rotate in the spot, what can damage the plastic cover	 
B) Double Swerve Wheels. 4 directional double wheel on each corner. The 2 wheels on each directional block move differentially	• High maneuverability like (A) • Double wheel configuration avoids rotation of the wheel on the spot	• Higher complexity and weight than (A) for adding extra wheels.	
C) Differential drive 2 Traction wheels on each side + 4 omnidirectional wheels in the corners	• Low complexity • Low weight • Rarely wheels rotate on the spot (can be avoided by High Level Controller). • Good Maneuverability	• Less traction than (A) and (B) because there are 2 motorized wheels and the weight is shared with non-motorized wheels. • The robot has to rotate to change direction.	

With in-site Swerve wheel rotation it destroyes the 37 micron film in seconds and the 125 microns film in some minutes. With combined linear + rotational movement holes in the plastic only appear where there were small stones or big dust particles.

- **Castor platform.** Kinematic configuration: 2 fixed + 2 castor wheels. Weight ~500Kg

Test was made only with 125 micron thickness. There are situations where the fixed wheel rotates in place, so the results are equivalent to test with AGVS.

- **Robotnik RB1 robot.** 2 traction wheels + 3 omni wheels. Robot weight ~30Kg + payload 62Kg

Table 3.2. Test over plastic cover

Type of Movement	Castor	Swerve/fixed	Omni wheels
Linear + rotational	Damage if small pebbles and granules	Damage if small pebbles and granules	Damage if small pebbles and granules
Rotation at low radius	Damages in some minutes	Damages in few minutes	Damage if small pebbles and granules

Test is made only with 125 micron thickness. It is possible to make holes only in places where there are small stones or big dust particles. In this configuration is is not possible to make the omni wheel rotate on the spot so a test was made with one omnywheel rotated by hand, but there was no extra damage to the over surface.

Next table sumarizes the results of the test regarding type of wheel.

Considering the previous studies the selected configuration for V1 prototype is (C) Differential Drive, because it is lighter and simpler and avoids the problem of the wheel rotating on the spot.

The final design is a platform with 4 omni wheels (one on each corner) and two driven wheels at the middle of both sides of the platform. There could be alternative configurations with castor wheels instead of omni since this configuration avoids corner wheels to rotate on the spot.

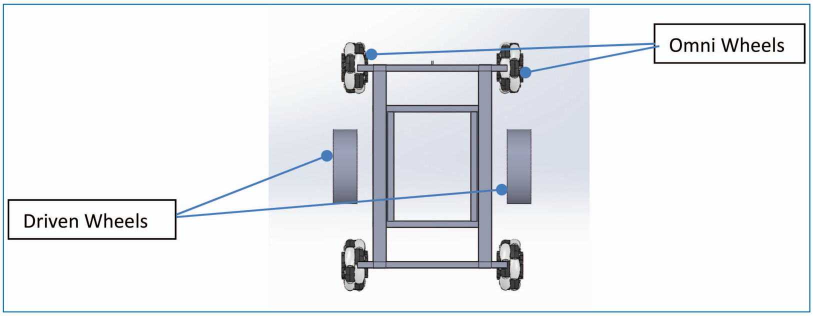


Figure 3.45. Wheel configuration.

This platform configuration needs that all omni wheels are in contact with floor, to be sure of that, at least one of them has to be capable to adapt to small height variations, so an oscillation axle has been designed.

Regarding driven wheels, they include a 500W pancake type motor with a solid rubber wheel with 220 mm in diameter.

The electrical hub has a 6:1 gear reduction, giving a max torque output of 37 Nm. The wheel is mounted in a suspension arm and, in order to be capable to test different suspension configurations for this first prototype, different air shock absorbers can be mounted. This shock absorbers must apply a force to

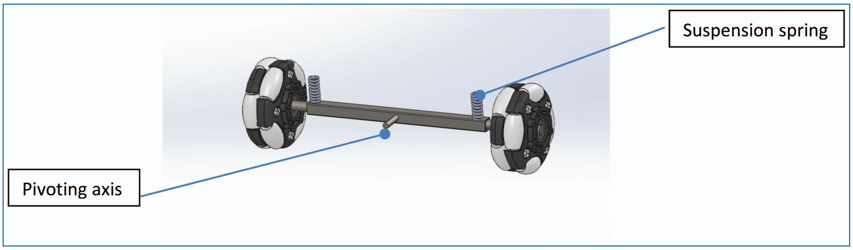


Figure 3.46. Oscillation Axle for Omni-Wheels.

the floor so the wheel friction forces ensure enough mechanical traction to the platform.

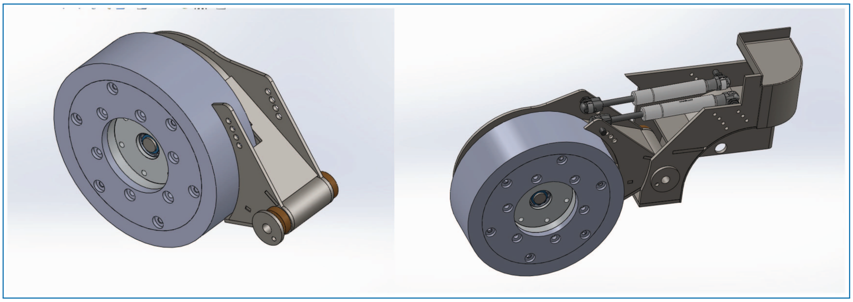


Figure 3.47. Driven wheel and its suspension.

3.1.15.2 Frame and covers

The frame of the platform is designed using rectangular steel tube. This type of structure is intended to provide enough rigidity to the platform without adding unnecessary extra weight to it. The resistance of the platform has been evaluated using finite elements analysis.

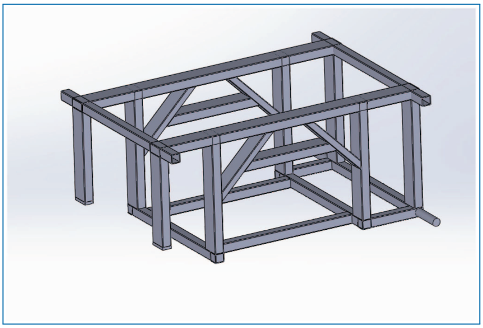


Figure 3.48. Steel tube frame.

The platform has to be easy to decontaminate so all the boxes for electronics are designed to have IP65 sealing.

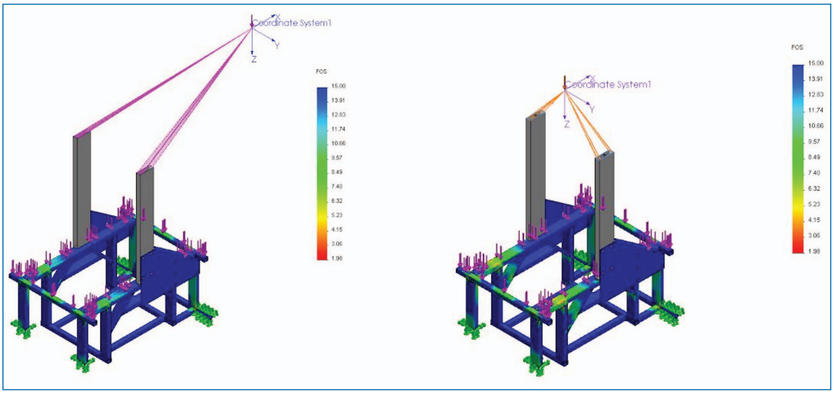


Figure 3.49. Steel tube frame Finite Elements Analysis under different loads.

The mobile platform will mount two Hokuyo UST Lasers, mounted on rear-left and front-right corners of the platform, providing a full vision angle around it. This lasers need to have full view without colliding with any part of the robot so, an air gap is needed in the lateral covers of the robot to allow laser beam to pass. Lasers are installed under top cover, in order to protect them from direct dust.

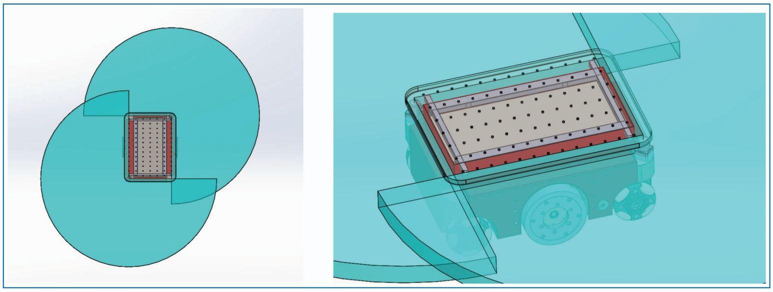


Figure 3.50. Laser range.

3.1.16 3D CAD Drawings, Manufacturing Drawings and List of Part for V1

The mobile platform for the first prototype has been designed.

The results are shown in attached documentation:

- 3D CAD models
- 3D CAD drawings
- Electrical drawings
- List of parts

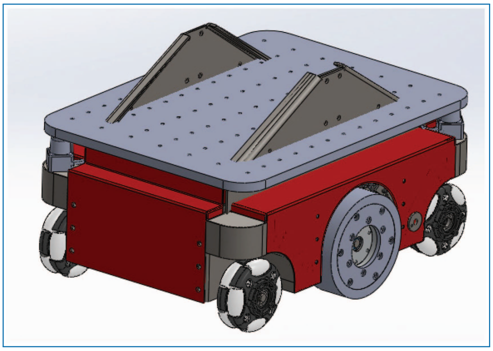


Figure 3.51. Mobile Platform.

3.1.17 Outlook and Future Work to be Carried Out

This deliverable shows the result of the work done during tasks 4.1 in order to create the first version of the platform. This work has been done in parallel with the work performed to design the rest of the subsystems, including the coordination work made in the integration workpackage WP3, so this WP is interconnected with the others.

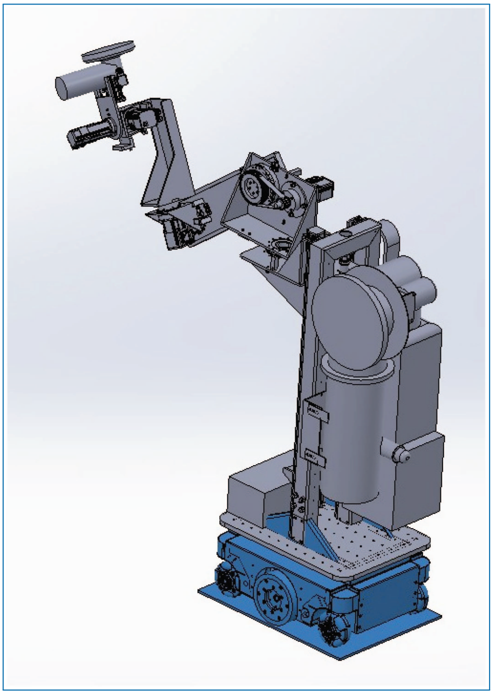


Figure 3.52. Mobile Platform in Bots2Rec first prototype.

Some problems have been encountered due to delay in decisions regarding requirements but they are not significant. Another delay has come from the problem encountered in arm definition: there was no commercial model able to fulfill the requirements and a new design has been done, so this affected the integration with the mobile platform and produced a delay of 1 month in integration of this subsystems with the others. We think this delay, as it is the first version, is not affecting the success of the project.

3.1.18 Summary and Conclusion

This deliverable achieved its objectives and provided a detailed design of the platform. With this design it is possible to manufacture a first mobile platform prototype able to fill the technical requirements and to be integrated with the rest of subsystem to build Bots2Rec V1 system.

Next steps are to manufacture the platform, test it with "dummy" weight to validate its performance, and integrate it with the rest of the subsystems. This project include several design cycles to future error corrections or improvements are expected for the next prototypes.

Deliverable D4i.3
Di4.3 Mobile platform V1 manufactured and ready for subsystem test

Authors: Miguel Moreno and Tim Detert

3.1.19 Deliverable in the Context of the Work Program

This internal deliverable is an output from *Task 4.4 Production and assembly of the mobile platform* to show the manufacture of the mobile platform for the first prototype (V1) of the Bots2Rec platform. It uses the input from previous tasks 4.1 4.2 and 4.3 and the information from deliverable *Di4.1 3D CAD drawings, manufacturing drawings and list of part for V1*.

The core part of this deliverable is the manufactured subsystem prototype ready to be tested. This report contains the explanation of the manufacturing process. Following to this deliverable is the testing of the Mobile platform individually, and then its integration with the rest of subsystems included in First prototype.

3.1.20 Methods and Work Carried Out

To reach this deliverable it has been required the input from task 4.1, 4.2 and 4.3 and the information in deliverable *Di4.1 3D CAD drawings, manufacturing drawings and list of part for V1.* As a result of the work in these tasks the procurement of some materials started before Di4.1 was finished.

The gathering of materials have been done from regular suppliers of Robotnik as most of the electronics components selected were already working inside robots of Robotnik product range.

To show the manufacturing process it has been divided between Mechanis and Electronics.

3.1.20.1 Mechanical Construction

Starting from the drawings of deliverable *Di4.1 3D CAD drawings, manufacturing drawings and list of part for V1.* The manufacturing process of different parts has been performed at Robotnik facilities but also at the facilities of different local Machining Workshops.

3.1.20.1.1 Frame

The frame has been designed to support high payload: the weight of the arm, tool, slider, aspiration system and extra elements.

The frame of the platform was designed using rectangular steel tube, it was assembled by Arc Welding. This type of structure was selected due to:

- High MOI (moment of Inertia) with low weight.
- Easy gathering of the material, construction and modification

The resistance of this chassis was evaluated using finite elements analysis, as shown in Di4.1, and has been tested as described in D4.1.

Once finished frame has been treated with a passivation process to be protected against rust and painted.

The heaviest component that the frame has to support is the slider, that's carries the weight of the arm to the platform. To hold this slider and transmit the weight and torque to the structure, two support brackets have designed.

These brackets are made of folded carbon steel (ST 37) sheet, the 5mm sheet is folded to provide rigidity and to add two different mounting surfaces.

3.1.20.1.2 Wheels

There are two types of wheels: four omni-wheels in the corners and two traction wheels in the sides, as shown in the next drawing.

Figure 3.53. Welding process details.

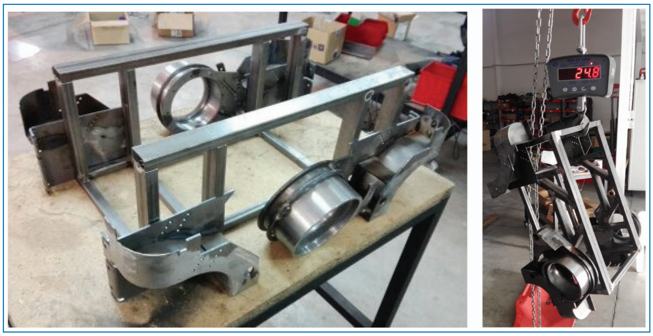


Figure 3.54. Frame before surface treatment.

Figure 3.55. Frame after being blued and painted.

The four omni-wheels have an inside bearing to provide free rotation around its central axis so they provide free movement in X axis, and Polyurethane (PU) rollers along its external circumference to provide free movement in Y axis. Omni wheels

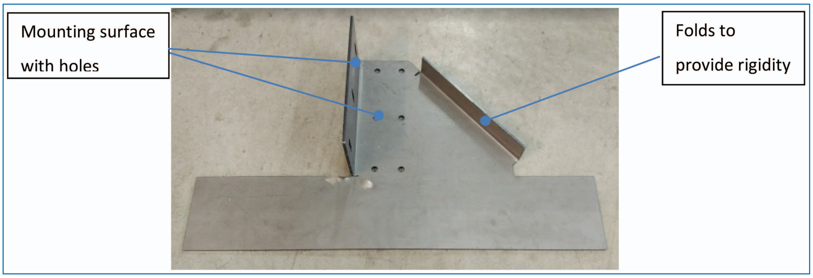


Figure 3.56. Supporting bracket for the slider.

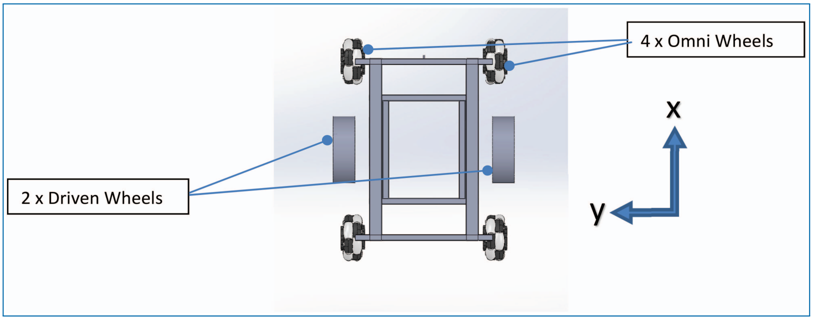


Figure 3.57. Wheel configuration and robot axis.

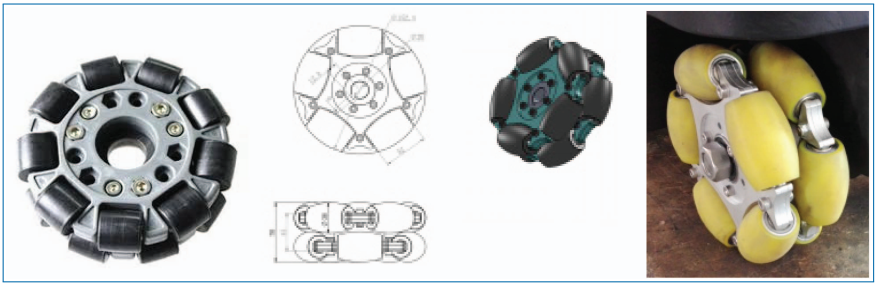


Figure 3.58. Regular size Omni-Wheel, and Bots2Rec Omni-Wheel.

have been ordered directly to a regular supplier but with a size bigger than other Robotnik robots to allow higher step crossing.

Traction/driven wheels have been developed by Robotnik and have a built-in gearbox and motor inside to provide up to 1000W of power, and an encoder to measure and control wheel movement.

The outer moving part of the when is a lathe-machined iron hub with a PU coat.

Driven wheels are mounted in a suspension system consisting on a Rocker Arm made of steel and a spring. The wheel inner hub is a lathe machined cylinder soldered to the rocker arm.

Figure 3.59. PU outer wheel and encoder of the driven wheel

Figure 3.60. Plinth used for soldering rocker arm to Lathe machined motorwheel hub.

Figure 3.61. Hub and Rocker arm finished with Bronze bearing inserted.

The rocker arm is attached to the robot frame with a bronze bearing joint and is pushed to the ground by gas springs. The springs can be mounted in different positions to allow different forces, depending on the robot load.

3.1.20.1.3 Covers

The covers are designed to protect the platform avoiding external elements to enter the platform. It has been decided that electronics are mounted inside sealed boxes to avoid contact with dust or water so external covers are not needed to be IP65 but they have to be easy to decontaminate.

The top cover is a ST37 steel 4mm plate. Its corners are rounded to facilitate rotation in narrow corridors. As the robot is a first prototype, an array of M8 threads

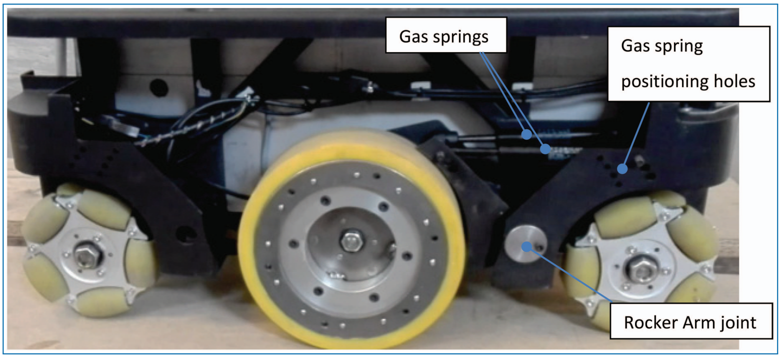


Figure 3.62. Rocker arm.

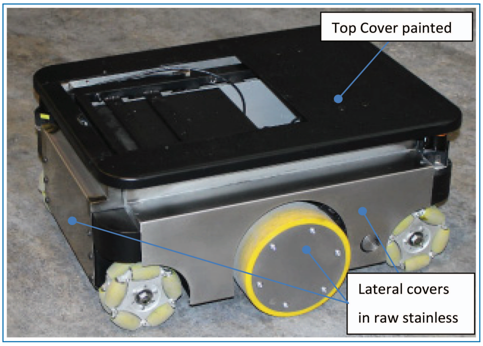


Figure 3.63. Covers.

are done in the top to facilitate attaching different elements, these holes will be sealed in future versions to avoid water splashes to enter.

The lateral covers are made of 1 mm stainless steel sheet folded. They are four independent covers to facilitate independent access to different parts of the mobile platform: front and back cover to electronics boxes and right and left covers to driven wheels and suspension system.

Driven wheel access has also been protected with the same type of stainless steel cover.

3.1.21 Mobile Platform V1 Manufactured and Ready for Subsystem Test

The mobile platform for the first prototype of Bots2Rec has been manufactured and it is ready for testing.

General parameters of finished platform have been measured:

Length: 760 mm
Width: 595 mm

Figure 3.64. Mobile platform V1 manufactured and ready for subsystem test.

Height: 355 mm
Weight: 95 kg

3.1.22 Outlook and Future Work to be Carried Out

This deliverable shows the result of the work done during tasks Task 4.4 Production and assembly of the mobile platform.

The manufacturing processes are not different from the ones used in other Robotnik mobile robots, except from the structural frame, as this kind of steel tube frame is normally not used, and so has occupied more time than expected but not adding a delay to the process.

The manufacturing process has suffered different problems that cannot be considered unusual for a prototype development process.

- Some delay on the decisions about the interfaces between the mobile platform and other subsystem have delayed the process of manufacturing. Specifically the position and configuration of the arm was defined later than expected, and the use of the inner space of the platform for the electronics has been changed during design and manufacturing process.
- It have been a delay due to problems of communication with omni wheels supplier, it is due to the fact that there is a very small number of providers of this kind of material and are based in China. It is expected that this will not

be a problem in future versions as it is planned to have stock of this type of wheel once it is validated by the complete robot tests.

- The covers attachment design has suffered small redesign due to redesign of V1 prototype redesign of cable routing.

3.1.23 Summary and Conclusion

This deliverable achieved its objectives and provided the manufacture process of the mobile platform. It has been shown the construction details and the solutions used to pass from the CAD and manufacturing drawings to a working prototype.

Next steps are to test the platform, to validate its performance, and to integrate it with the rest of the subsystems.

3.1.24 Robotic Arm

Deliverable Di5.1

Customization of the robotic arm 3D CAD drawings, manufacturing drawings and list of part for V 1

Authors: Francesco Becchi, Tim Detert

3.1.25 Deliverable in the Context of the Work Program

The Scope of this internal deliverable is to present the CAD design of the robot arm developed within the scope of WP5. The deliverable is an output from Task 5.1 "Design of the robotic arm first prototype (V1). It uses the input from previous deliverables "Di3.1 Specification of the system architecture and interfaces" and "Di3.2 Specification of the technical requirements for the V1 prototype".

This deliverable contains the CAD files, CAD drawings, part lists and electrical drawings necessary to manufacture the first version of the robotic arm, as a part of Milestone 1 (Overall system layout and design of the first prototype and central system finished). The following section introduces the guidelines defined in the arm design trough first conceptual design. The third section details the reference final design.

3.1.26 Methods and Work Carried Out: Main Design References

The original arm layout was based on two main links (upper arm, forearm) with a 2 dofs shoulder, single dof elbow and 3 dofs wrist. The link length was defined so to match the reach requirement defined in the system specifications (2D simplified models were used for such purpose). Local motor+gearhead positioned on each

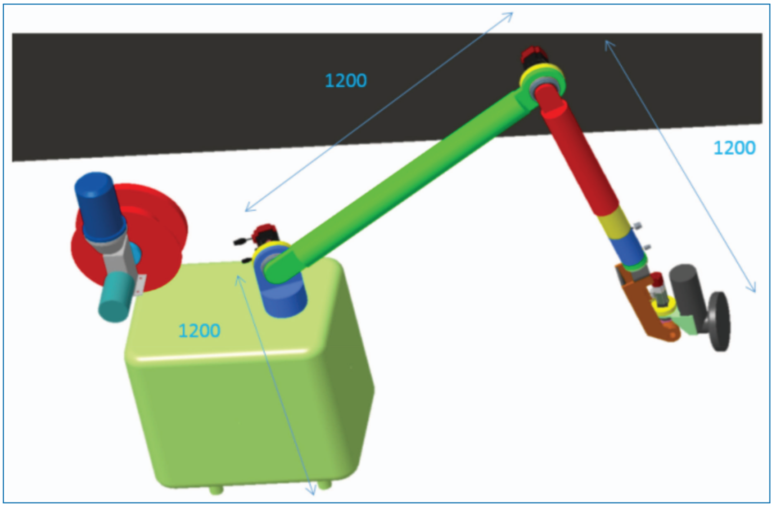


Figure 3.65. First arm conceptual design.

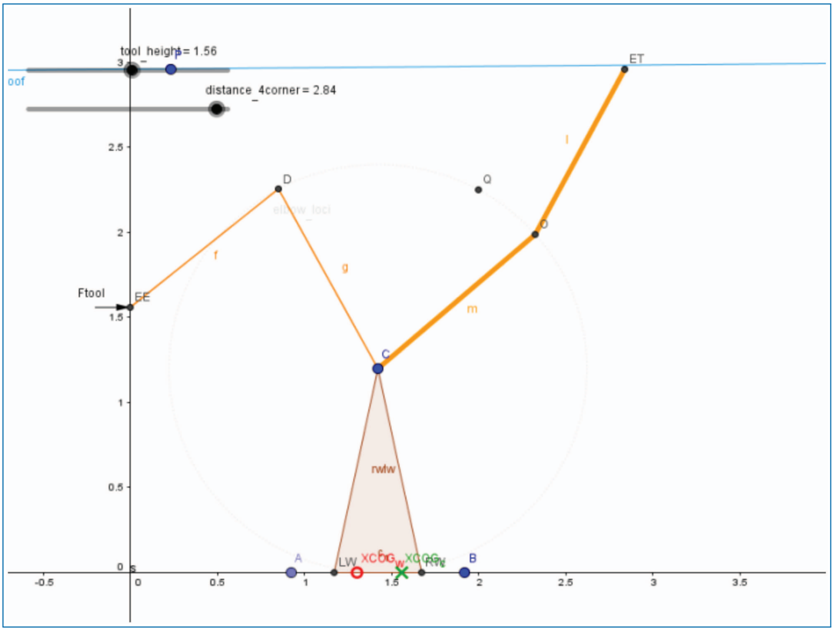


Figure 3.66. First arm 2d reach verification.

joint was the reference solution. An axial compliant slider was also included in the forearm to allow tool compliant control.

The operational requirement in limited/narrow spaces as corridors took to an alternative design where the articulated links of the robot arm were significantly reduced but the needed vertical reach was ensured adding a vertical slider.

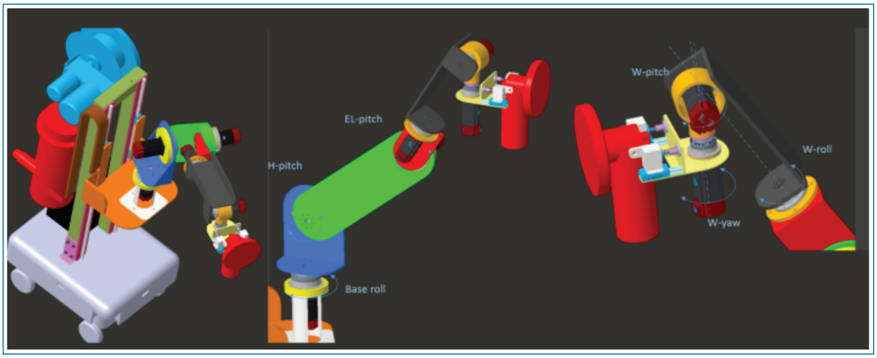


Figure 3.67. Second solution conceptual design.

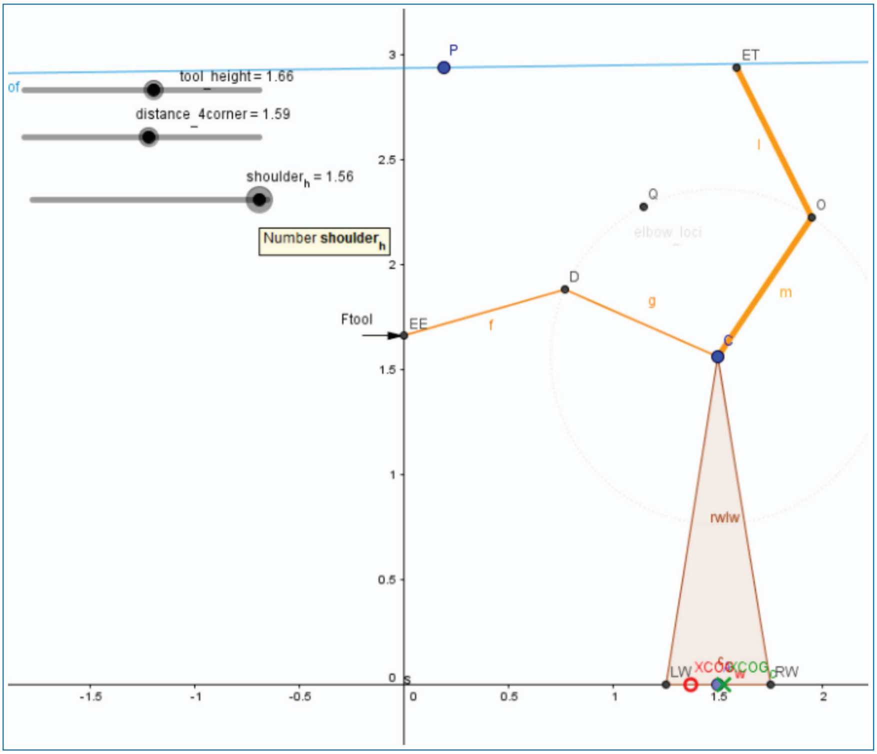


Figure 3.68. Second solution 2d reach verification.

3.1.27 Final Design

This section details de final design of the robot arm. In line with the updated conceptual design introduced in the previous section the reference design is based on a 6 dofs serial arm integrated on a vertical slider frame. All system dofs are controlled in closed loop with a brushless DC motor.

The following pictures give an overview of the robot arm including the slider and identify each DOF.

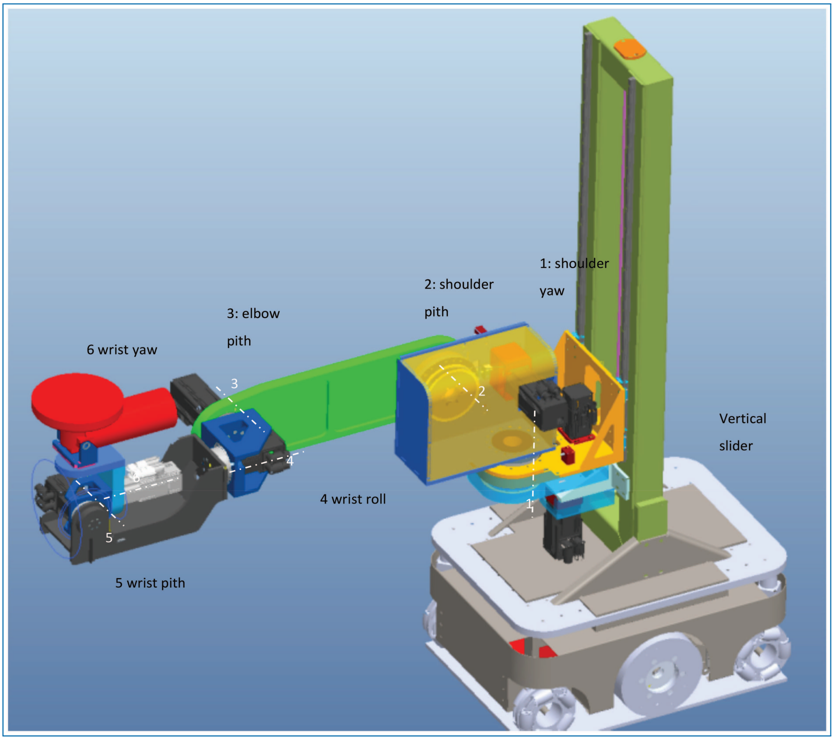


Figure 3.69. Overall view of the robot arm final design.

Each dof is based on a Harmonic driver gearbox with integrated crossed roller bearing. The Gearbox and supported bearing were sized according to the following load conditions:

- Robot arm own weight;
- Robot arm configuration: fully extended (as shown in the above picture);
- Safety factor on tool weight 2 (10 kg);
- Tool/wall-ceiling interaction force 80 N.

The table that follows summarize the load condition considered in the design.

NOTE: coding standard used in the design is based on TLABS internal QA rules. For quick reference the BOTS2REC project ID is 0000120 (internal job). Parts are identified with the "P" letter followed by a serial, sub-assembly with a "G" and top level assembly with "A".

Quick Overview	Gearhead			Torque				Bending			
	Harmonic drive model	Max output Torque (Nm)	Max bending torque (Nm)	Arm own weight (Nm)	Tool interaction force (Nm)	Total (Nm)	SF	Arm own weight (Nm)	Tool interaction force (Nm)	Total (Nm)	SF
YAW UNIT	HF UC-17-50-2UH	54	64	24.72	8.8	33.52	1.61	24.72	14	38.72	1.65
PITCH UNIT	HF UC-17-50-2UH	54	64	34.53	12.4	46.93	1.15	34.53	15.6	50.13	1.28
ROLL UNIT	HF UC-25-50-2UH	98	156	41.45	8.8	50.25	1.95	127.53	32	159.53	0.98
ELBOW UNIT	HF UC-32-160-2UH	372	313	158.22	48.8	207.02	1.80	158.22	57.6	215.82	1.45
SHOULDER	HF UC-40-100-2UH	617	850	366.89	112	478.89	1.29	129.36	120	249.36	3.41
BASE ROLL	HF UC-40-100-2UH	617	850	0.00	112	112.00	5.51	467.58	120	587.58	1.45

3.1.27.1 Vertical Slider

The vertical slider is based on a welded and machined stainless steel frame. Two parallel 15 mm four races guideways with 2 cart per rail support the main arm frame. The displacement of the vertical slider is made with a rotating trapezoidal screw driven by a brushless motor. The translating brass nut is integrated in the robot arm support frame.

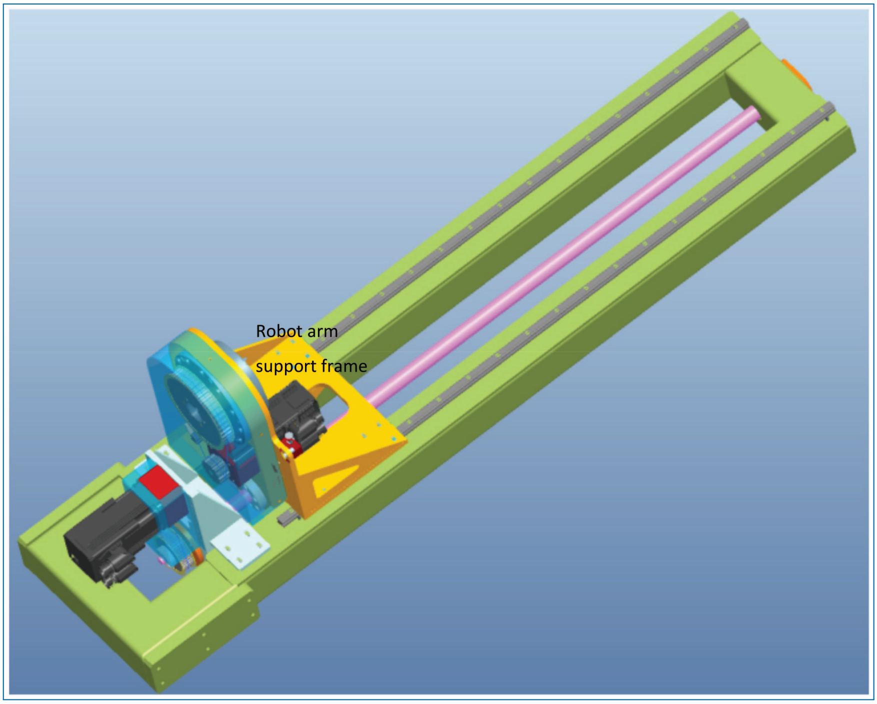


Figure 3.70. Vertical slider (T000120G001).

The support frame is made out of a welded 6000 series aluminum alloy machined on its main mating reference surfaces.

As visible in the detailed view that follows the shoulder yaw actuation is also integrated in the support frame as follows:

The HFUS gearbox is assembled on the frame so to support on its output flange the main shoulder frame. The driving motor is positioned vertically behind the shoulder frame and connected to the HFUS input flange with a timing belt transmission.

NOTE: all the timing belt transmission considered in the design are protected with a dedicated carter for safety reason.

The two red block visible in the picture are the adjustable end of stroke of the shoulder yaw. An inductive sensor is also included to perform motor calibration.

Figure 3.71. Robot shoulder support frame (T000120P002).

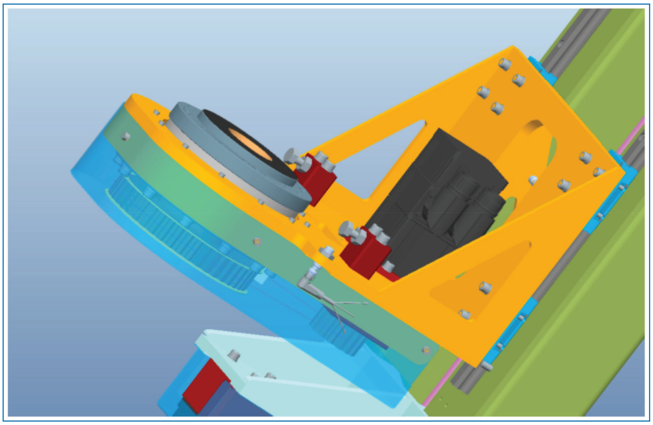


Figure 3.72. Shoulder yaw actuation.

3.1.27.2 Main Shoulder Frame

Following a similar arrangement than the main arm support the main shoulder assembly is made out of a welded and machined aluminum alloy frame that integrates HFUS harmonic drive and its driving brushless motor.

3.1.27.3 Robot Arm Elbow

The robot elbow assembly is based on HFUC 32 harmonic drive with integrated brushless motor on the input flange. The elbow pitch is connected to the shoulder pitch with a AL6082T6 machined aluminum alloy frame (T0012P008). The elbow output supports with a machined interface frame a similar actuation unit with an HFUC25 and its integrated motor used as wrist roll.

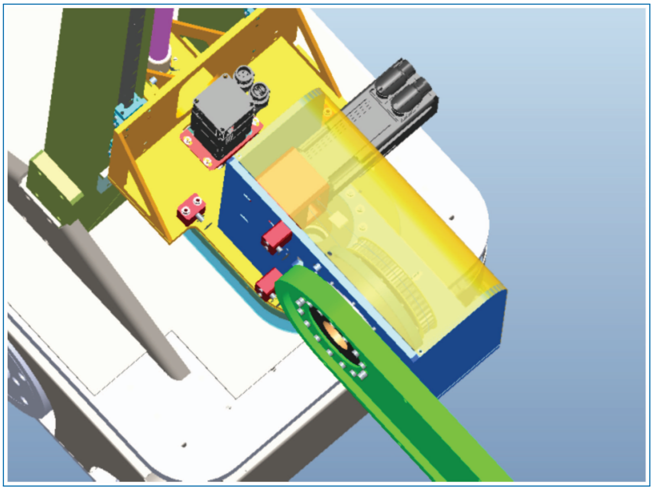


Figure 3.73. Main shoulder assembly (T0000120G006).

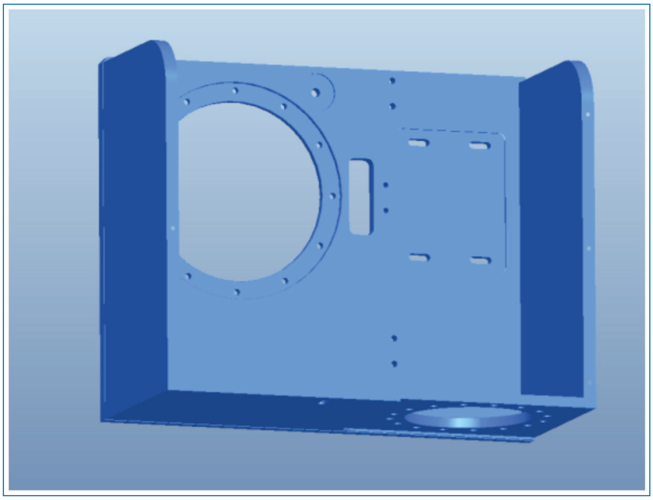


Figure 3.74. Robot shoulder main frame (T000120P060).

3.1.27.4 Robot Forearm/Wrist

The robot forearm structure is based on a special "cradle" aluminum frame designed for an optimized tool attitude control on vertical walls. The distal end of the forearm supports the last two wrist degrees of freedom both based on HFUC-17 harmonic driver gearhead.

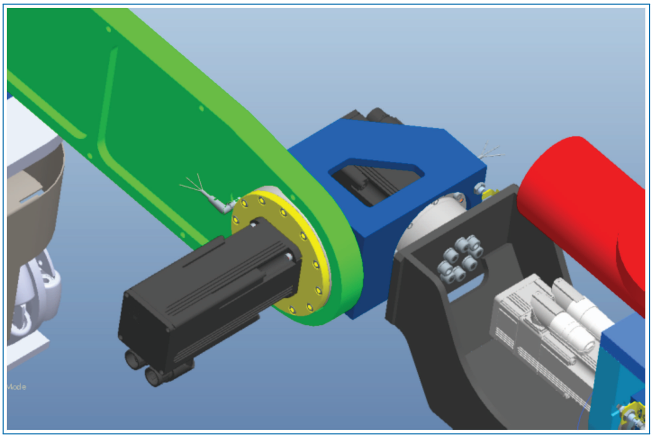


Figure 3.75. Elbow pitch joint and wrist roll.

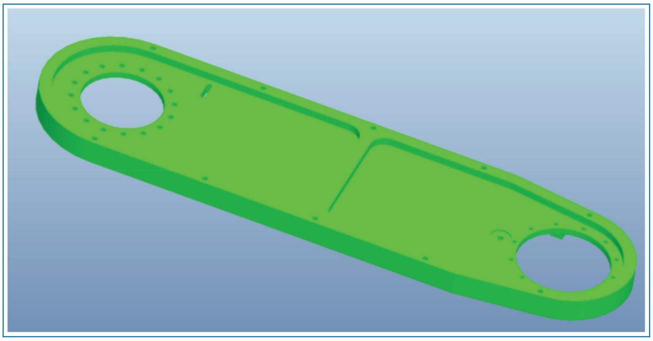


Figure 3.76. Upper arm frame (T000120P008).

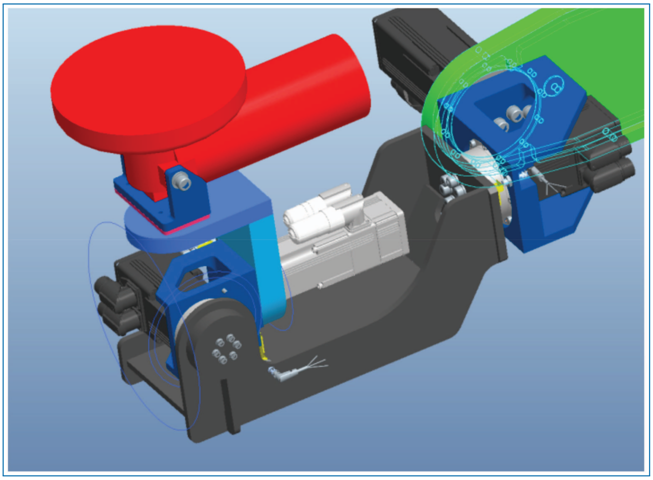


Figure 3.77. Forearm wrist layout.

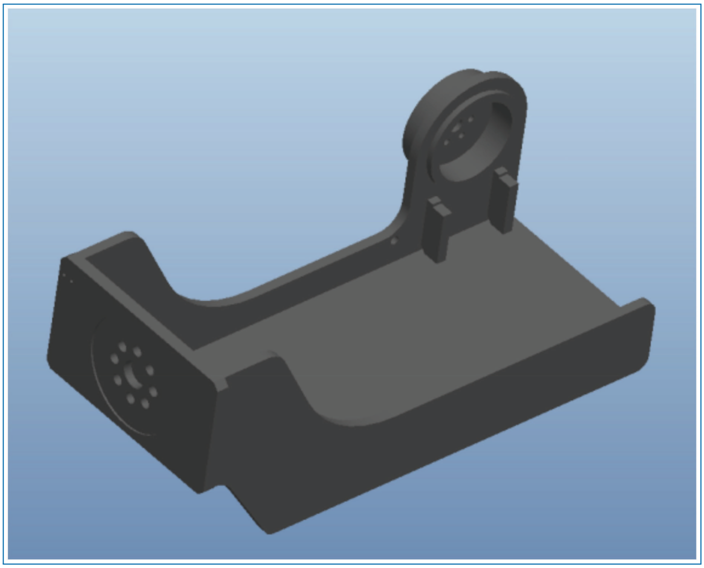


Figure 3.78. Forearm cradle frame (T000120P065).

3.1.28 Outlook and Future Work to be Carried Out

This deliverable shows the result of the robotic arm design performed during tasks 5.1. It has been done in parallel with the design of the other subsystems and the overall system integration in WP3. The overall design process was delayed with respect to the time plan: Difficult conceptual considerations for the robotic arm and controversy discussion led to a longer conceptual phase. No commercial model was able to fulfill the requirements and a new design had to be considered.

After finishing the design, the arm implementation has started but the targeted Deliverable Di5.3 ("Robotic arm V1 manufactured and ready for subsystem test", due 01.11.2016) and D5.1 ("Robotic arm tested and ready for integration …", due 01.12.2016) will be delayed by 2-3 month. However, the current time plan should allow to keep the targeted Milestone 2 ("First Prototype available and functional") by end of 01/2017. The Christmas break and planned buffer during the end of the year will be used for the realization of the robotic arm.

3.1.29 Summary and Conclusion

The arm design was performed based on the technical requirements. After conceptual considerations mainly of the kinematic structure (considering workspace, reach

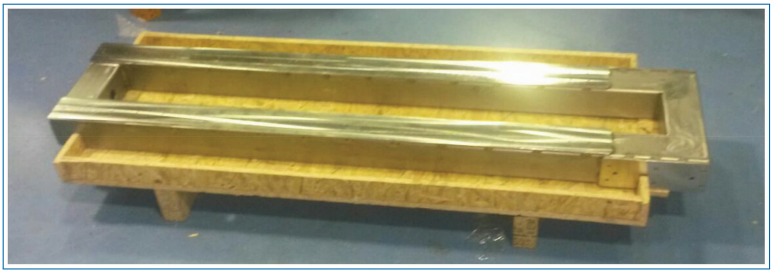


Figure 3.79. Arm mechanical integration (shoulder and elbow).

and payload/operational forces) the final design was implemented considering all technical specifications. The design steps were iterated in discussion with the partner and considering the relevant interfaces for the system integration. The design is finished and first steps towards the realization have already been performed. The following realization and testing is delayed due to an extensive period of the conceptual design, but the targeted first prototype of the robotic system will nevertheless be finished in 01/2017 by speeding up the arm manufacturing and using some buffer time at the end 0f 2016.

Deliverable Di5.3
Di5.3 Robotic arm V1 manufactured and ready for subsystem test

Authors: F.Becchi

3.1.30 Deliverable in the Context of the Work Program

Scope of this internal deliverable is to summarize the integration (mechanical and electrical) of the first prototype of the robot arm. The following section reports views of different stages of integration of the robot arm.

3.1.31 Mechanical Integration

All custom made welded and machined component with commercial components are assembled in the TLABS workshop following the robot arm design and documentation.

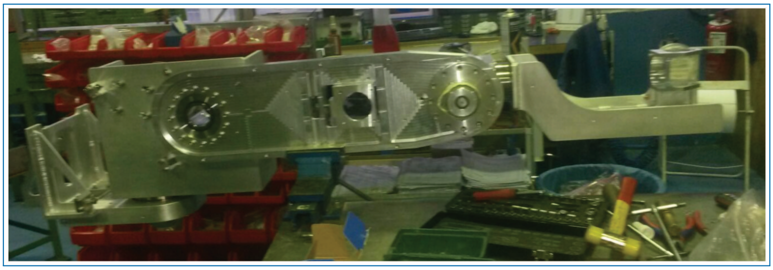


Figure 3.80. Arm mechanical integration (shoulder and elbow).

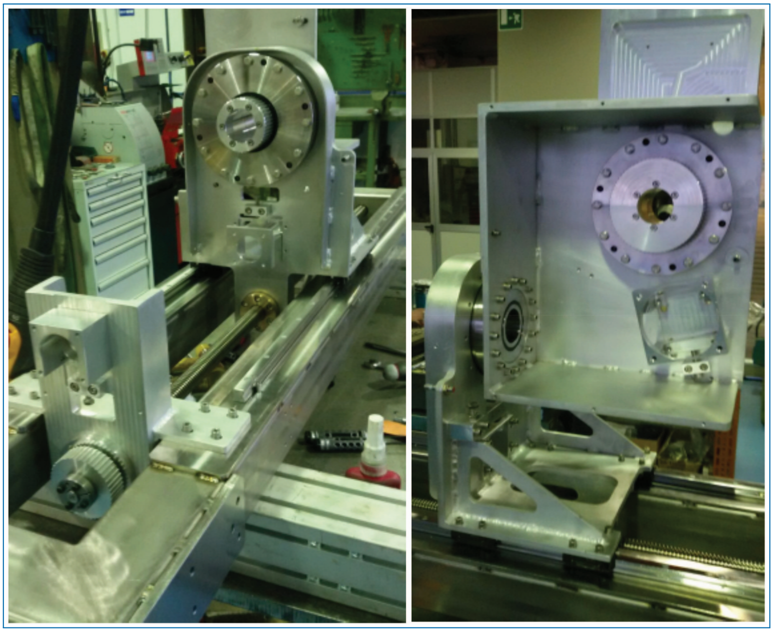


Figure 3.81. Vertical slider and shoulder pitch transmission details.

A temporary support frame made with a welded interface and a large assembled frame is also prepared to position the arm and its vertical slider support in its nominal configuration to perform electrical integration of arm motor and sensors, auxiliary subsystems , B1 and B2 cabinet in line with the robot assembly layout.

3.1.32 Electrical Integration

The two B1 and B2 arm electrical cabinets are first assembled on the cabinet back plate and then integrated with all cables and connectors in the cabinet. First cables are routed on the arm support structure following the path planned in CAD.

Figure 3.82. Complete arm structure on dummy frame structure ready for electrical integration.

Figure 3.83. First cable routing.

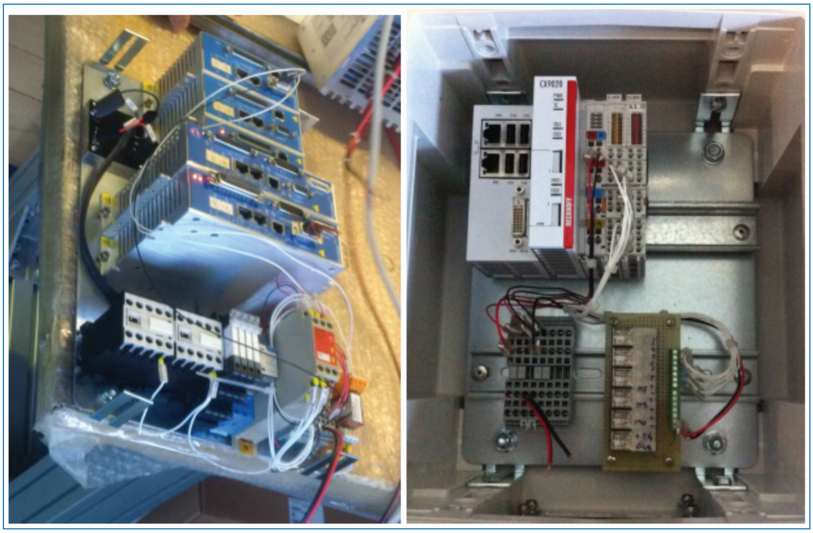


Figure 3.84. B2 and B1 cabinet first integration.

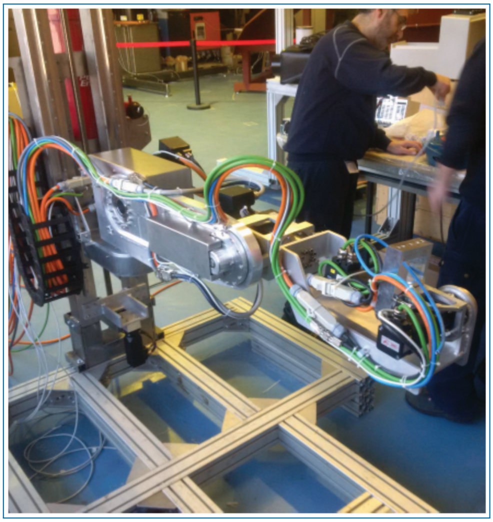


Figure 3.85. Arm cabling nearly completed.

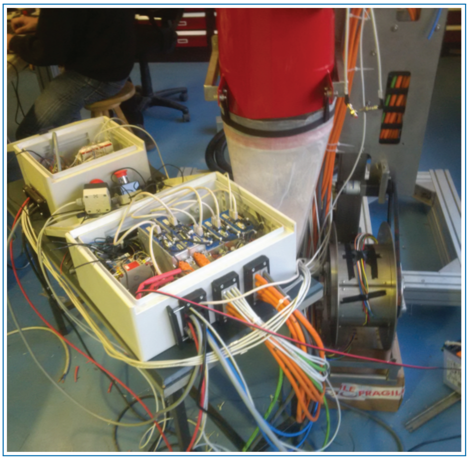


Figure 3.86. B1 and B2 cabinet in integration.

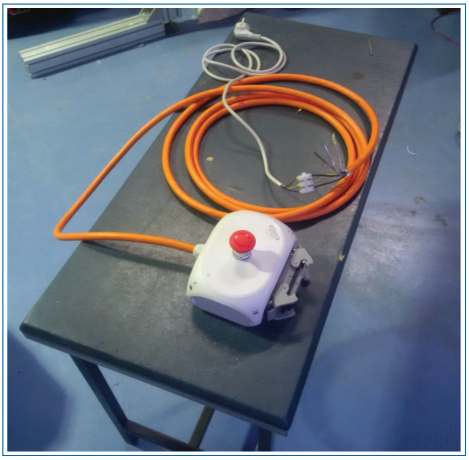


Figure 3.87. Terminal box.

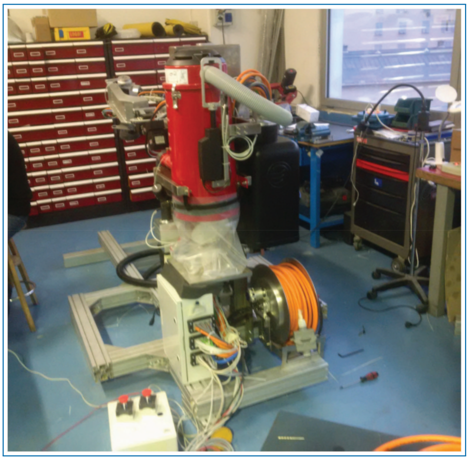


Figure 3.88. Integration complete (rear view).

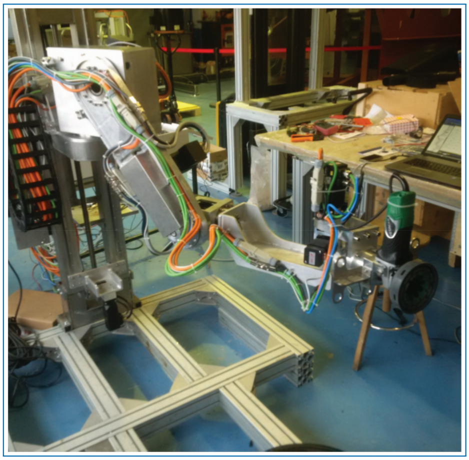


Figure 3.89. Integration complete (front view).

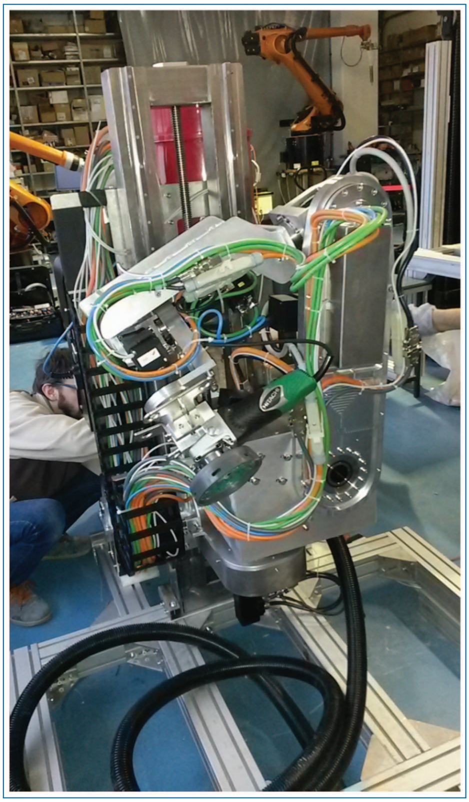


Figure 3.90. Arm in “storage” position.

3.1.33 Outlook and Future Work to be Carried Out

After completing the mechanical and electrical integration and the configuration of the different modules, a preliminary stand alone testing of the robotic arm and its functionalities is foreseen.

3.1.34 Summary and Conclusion

This internal delivery resumes with a sequence of shots made in the TLAB workshop the robot arm mechanical and electrical integration.

3.1.35 Radar Sensors

Deliverable 4.2
Sensor system for environmental perception ready for implementation

Authors: Dr. Matthias Rabel, Masrur Doostdar

3.1.36 Deliverable in the Context of the Work Program

Positioning, Navigation and Control of automated equipment relies on sensors detecting the environment. Within the Bots2Rec project a robot shall be constructed that allows remote operation and processes predefined tasks. The field of operation is asbestos removal within buildings, thus it shall work in an environment where humans hardly can work in. This deliverable focuses on the mobile part of the robot. Sensors shall be able to detect walls, obstacles, steps and holes and thus enable the mobile units to move without misadventures. Also the operators should be able to visually check the environment.

3.1.37 Methods and Work Carried Out

There is a variety of sensors available to detect objects around a robot. First, the given constraints have to be analyzed. Besides several use cases, overall, the robot shall be realizable in terms of cost during the project and afterwards in real environments. As orientation the robots cost shall be limited to about 30.000Ł. This estimate does not yet contain expensive sensor systems. Methodically, a top down approach seems to be straight forward to narrow possible options down.

First, the robot must be moved or delivered to its field of operation. This must be possible using a remote control to move the robot. Possible required sensors are:

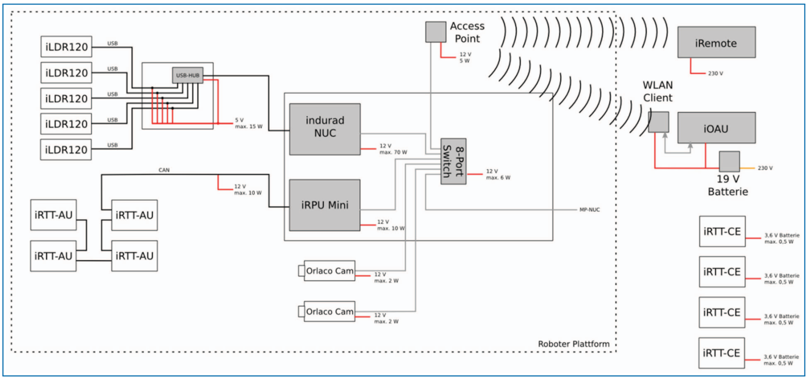


Figure 3.91. Sensor system layout, for mobile platform and robotic arm.

- Cameras so that the operator can see the surrounding
- Sensors to detect obstacles to prevent accidents, e.g., ultrasonic ranging, radars, lidar 2D or 3D, stereo vision cameras or time of flight cameras
- Indoor positioning systems, e.g. GPS-like systems working indoors; one technology known to measure distance is ultra-wide band radio ranging, measuring the time of flight of radio signals
- Movement detection sensors like acceleration sensors and gyroscopes

Second, it is worth looking out for other industries. Especially the automotive industry tries to detect the surrounding environment since several years. Gradually these systems become more and more complex. Modern vehicles have assisting systems using cameras, radars and ultrasonic devices. Infrared cameras are also being used to allow vision during foggy weather conditions.

Third, as the partner *indurad* focuses with its solutions on the mining industry with very tough environmental conditions, *indurad* is well aware that any optical system will not operate reliably. Optical sensors must be either cleaned repeatedly or protected using movable covers that can only be opened when the environment is clean. This limits possible measurement principles to radio links like UWB distance measuring or radar-based systems. Both are known to perform well in dusty, foggy and muddy environments. Nevertheless, cameras are still required to give the operator the option to see the environment.

3.1.38 Layout of the Sensor System

Figure 3.91 shows the general layout of the sensor system implemented on the current prototype V1.

Within the dashed area the mobile platform is shown. Grey colored infrastructure components are used to transfer and analyze the data. An access point is

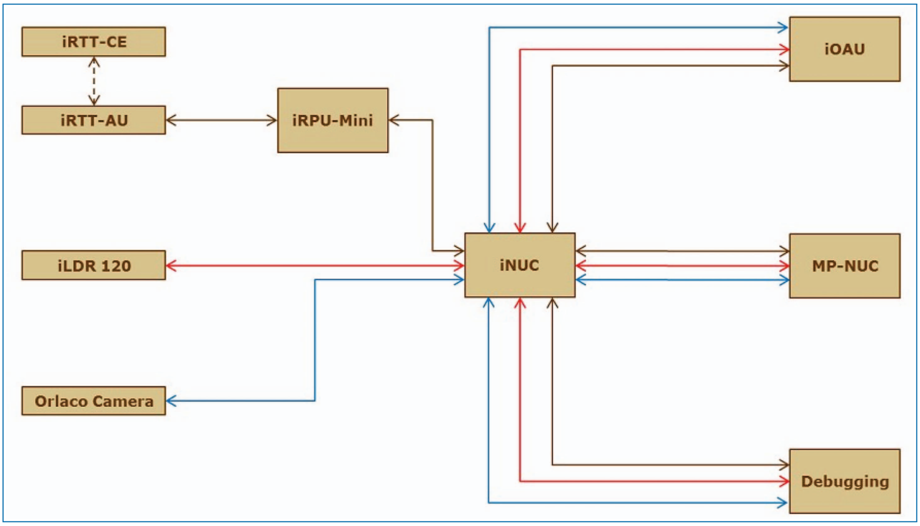


Figure 3.92. Signal and control flow.

mounted for wireless data transmission to the external system components. The sensor system for environmental perception contains:

- 2 Cameras produced by Orlaco
- 4 Devices called iRTT-AU, short for "indurad Radio Transponder Tag – Antenna Unit". It uses an ultra-wide band radio for ranging.
- 5 iLDR120 "indurad linear dynamic radar". They are mounted on the robotic arm to monitor the process locally (see Task 5.2). Together with the robotic arm these sensors could also be used to scan the environment.

Additionally to this current setup up of the sensor system, typical automotive radar, measuring a 2D segment and a 360° scanning radar, measuring distances in a 2D plane, have been evaluated preliminary.

The data flow diagram shows the data path between the main systems. iNUC[1] is the central instance of the measurement system providing the interface to the MP-NUC (mobile platform – NUC), the user interface and debug interface. Additionally there is an external iOAU "indurad operator assistant unit", an operation panel with the user interface. The iRemote is another device that allows *indurad* to remotely analyze and debug the components.

1. "NUC" is an Intel compact computer that can be mounted on the robots platform.

3.1.39 Sensors Integrated to the Current Layout

3.1.39.1 Camera System Orlaco

The camera system is used to give the operator an environmental view and shall be used to check the result of the grinding process. Deliverable 4.2 focuses on the environmental view, deliverable 5.2 focuses on monitoring the process results, while using the same cameras. The cameras are available with 120° and 180° opening angle. Variants with 90°, 60° and 30° are planned by the manufacturer. The camera allows a video resolution of up to 960p with 45 frames per second. The housing is IP68 and IP69k specified. Thus, it can easily be used in dusty environments. The camera has a high dynamic range of $>$ 115dB and has a low light feature. Figure 2 shows the camera and a picture taken underground, with a 120° variant. The picture quality is quite good. The only area exceeding the dynamic range is at the dark corners of the image and at the light bulbs.

For now, the camera data is only intended for visual inspection. This might change later.

3.1.39.2 Ultra-Wide Band positioning system iRTT

Depending on the used definitions ultra-wide band (UWB) communication operates with a signal bandwidth of >=50MHz or >=500MHz. Bandwidths between 50MHz and <500MHz are named as wide band (WB) systems, whereas ultra-wide band uses >= 500MHz as bandwidth. The use of UWB radios is strongly limited to the intended use as described in the relevant European specifications (ETSI EN 302065). Indoor there are only power restrictions. Outdoor license free use is limited to handheld or vehicular.

UWB radios embed a fast running internal clock that is able to record timestamps on picosecond basis. Thus, the time of arrival of a message can be detected exactly. By exchanging data packets between the radio devices the time of flight can be calculated. This process is called "two-way double sided ranging", allowing to calculate the clock offset between the devices. The clock skew causing errors can be minimized. Exact measurements require a direct line of sight and ideally, multipath free environment. A theoretical distance accuracy of about 5 cm seems to be possible with a single measurement.

3.1.39.2.1 Setup and configuration of iRTT

The ultra-wide band positioning system iRTT (Figure 3.93) consists of iRTT-CE (Client Equipment), iRTT-AU (Antenna Unit) and its process control unit called iRPU-Mini. It requires additional components that must be installed at fixed locations inside the room the robot operates in. The iRTT-CE "indurad radio

Figure 3.93. Orlaco camera EMOS Ethernet; Example picture underground.

transponder tag – client equipment" is a battery operated device that can be used for this purpose.

The technology is applied within very robust housings that can be used in underground mining. Thus, there is potential to reduce its size for the second, final robot prototype 2. The antenna units are mounted on the robot, the distance between any of the antenna units shall be maximized, and also the mounting height must be variable to prevent symmetric axes or planes. E.g., if all four antenna units were mounted vertically along a line, then the system could not detect a direction, it could only detect the height and a radius. If all four antenna units were mounted within one plane then the height would be ambiguous: either the solution is above or below the plane. A way to eliminate this ambiguity is to use context information. Inside a room the robot will most likely not change its height very much. Anyway, in case of more complex rooms, the height should be detectable.

The four or more client equipment components are placed around the robot. They need to be fixed inside the room. These 4 devices can be used as anchor nodes. If the position of those four nodes is known, every node on the robot can be localized using simple trigonometric functions.

The selected mathematical algorithm is taking into account that the measurements might be wrong. Therefore an approximation based algorithm like Gauss-Newton is used. An initial localization is used to start the algorithm. The output is generated after about 50 cycles.

The results of all four measurements are evaluated against the known mounting places of the antenna units on the robot. This allows matching the robots shape into the found positions. Finally, the robots pose is determined. Additionally, an unscented Kalman-Filter implementation is used to track the position.

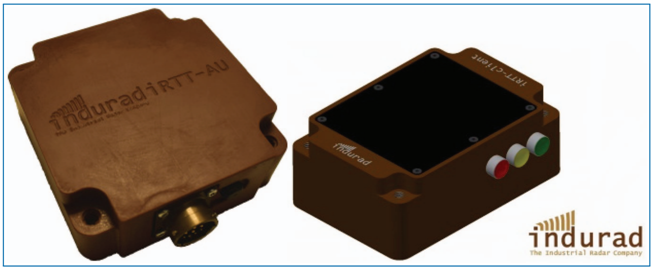


Figure 3.94. iRTT-AU and iRTT-CE.

Figure 3.94 shows a row of pictures with different positions of the robot. On the left, the calculated position is drawn. As additional information, the measured distances from any iRTT-CE to any iRTT-AU are drawn as circles around the anchor nodes (iRTT-CE). The large black dots are the iRTT-CE inside the room. The four colored dots are the iRTT-AU on the robot. It can be seen that the shown positions fit to the photograph.

Additionally, in Figures 3.95 and 3.96 circles have been driven and the robot was moved forward and backward. It can be seen that the measurements are repeatable. Nevertheless, the accuracy is just a rough estimation, since the robot could hardly be maneuvered in a circle with its remote control and also the algorithms are in an early stage of development

3.1.39.2.2 Perceptive Capabilities

Ultra-wideband ranging has been found to be quite sensitive in multipath environments and in environments with limited direct visibility between anchors and tags. The according situations are named LOS for "line of sight" and NLOS for "non line of sight". A number of possible design changes to improve the performance have been evaluated. Also, a system to analyze the positioning quality has been developed.

Hardware improvements

A second ranging system has been implemented using the ISM band at 2.4GHz. This allows for a higher output power of about 20dB compared to UWB. The longer wavelength allows a better visibility in NLOS situations.

An additional motion detection system is mounted to the robot platform. Measuring the acceleration will allow to calculate the motion sensor data and the iSDR data together in one model using Kalman-Filters. Furthermore, a hardware change on such a small robot would be possible due to the relatively short cables required. The anchors could be synchronized using hardware synchronization. This would allow almost synchronous operations. It reduces the measurement noise detecting the timestamps drastically.

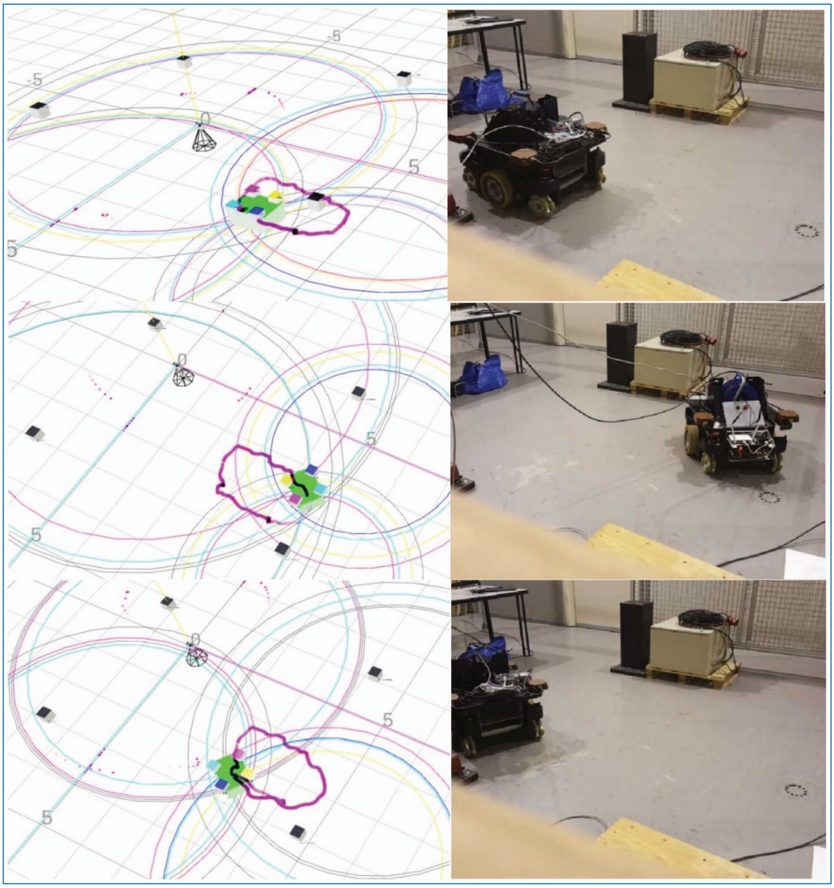


Figure 3.95. Robot position calculated/photograph.

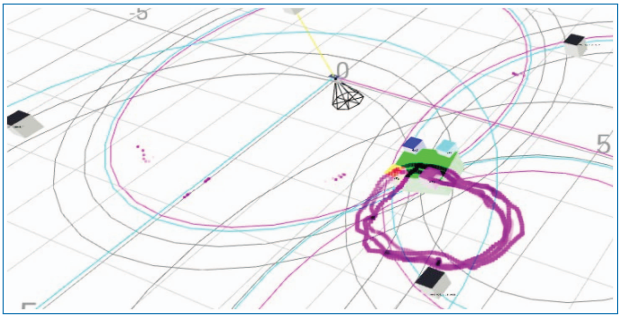


Figure 3.96. Repeatability: mobile platform driving circles.

Software improvements

Any type of ranging allows detecting a number of failures. First quality markers have been added. With every data packet these indicators are calculated, e.g., RSSI

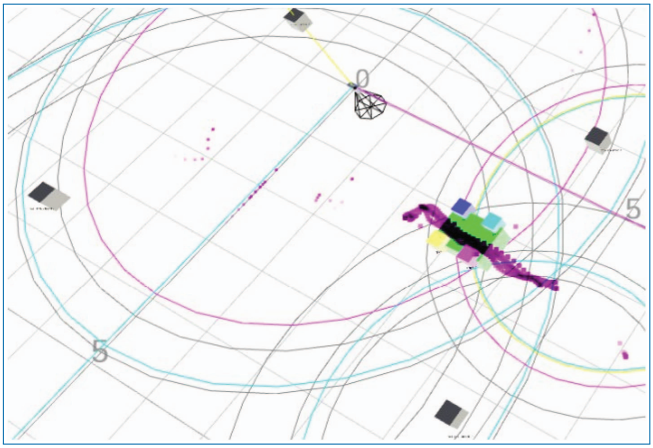


Figure 3.97. Repeatability: mobile platform driving for- and backward.

(received signal strength indicator. Second data analysis improvements have been realized to evaluate the measured sensor data, e.g., see Figures 3.97 and 3.99, both screen copies of an analysis tool. Within the analysis-tool, stored real-time data can be replayed forward, backward and with different speeds.

3.1.39.2.3 Accuracy

To verify the accuracy of the radio ranging technology a grid with squares similar to a chess board is defined. The squares are 0,5m x 0,5m. Additionally, on the robot the middle position of the robot is marked. Now, the robot can be moved exactly with its center along the chess square edges. On every node, where two lines cross each other, the robot will stop and a number of measurements are taken for statistical analyses. Figure 8 shows the white grid using the left and right 180° camera mounted on the robot. First trials have shown relatively strong deviations from the nominal positions.

In Figure 3.99 the first line shows the gyroscopes perpendicular to the robot plane. Mainly only noise can be seen. The second line shows the measured yaw value from the IMU. The third line shows the x/y coordinates of the robot and the last graph shows the deviation between the positioning and the estimated ground truth, derived from the camera pictures. It has been shown that a number of improvements must be developed, as the deviation of up to 1m is not yet acceptable. A major reason for the huge deviation is that on the second trial performed on the testing site in Valence now the mobile platform is mounted together with the manipulator, this causes numerous NLOS situations. For now there is no multipath filter enabled, although the measurement system has detection possibilities for multipath situations.

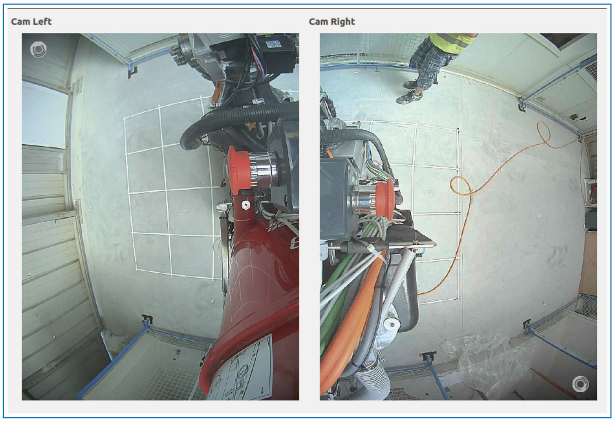


Figure 3.98. Accuracy evaluation using a grid.

Figure 3.99. Inertial data, position data and deviation between measurement and nominal position over time.

3.1.40 Sensors to Augment Environmental Perception

3.1.40.1 360° Scanning Radar iSDR

The iSDR is a rather large device optimized to detect objects in several hundred of meters. A rotating parabolic mirror focuses the radar beam. It is a highly configurable device that allows using the whole frequency range usable for vehicular

Figure 3.100. Indurads 360° scanning radar iSDR.

applications (76–81GHz). Its beam focus is about 1.4° (+/-0.7°). Its angular resolution is also about 1.4°. Recording the peaks with a mechanical angular resolution of 0.18° might allow detecting the angles quite exact. 5GHz as bandwidth allows unambiguous distance measurements down to 3cm. Rotation rates can be applied from 0 to 15 rounds per second (Figure 3.100).

Although these values are promising and tests have shown rather good results, the device is far too large and heavy to be used on the robotic platform of the project. Due to the fact that the device might be replaced with a far smaller variant it is still worth evaluating.

The iSDR output is a list of detected targets of every single measurement, together with its measurement angle. The list is truncated by a minimum and

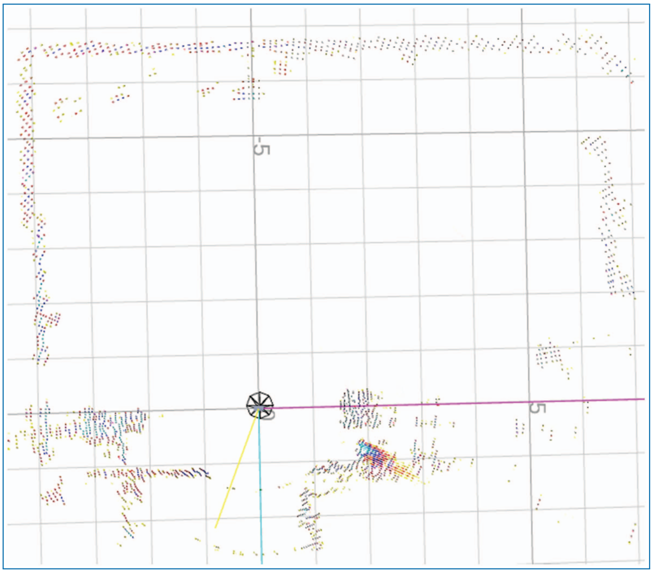


Figure 3.101. iSDR example of point cloud.

maximum distance. Also a minimal signal strength value can be configured. The detected outputs are passed with the signal strength in logarithmic scale. Figure 11 shows an example of such a point cloud. One grid square is 1m. It can be seen from the origin 1.5m down left and down right, there seems to be a circle. This is the set minimal distance, so the near multipath reflections of the antenna and random are suppressed. In the scope of task 6.2 these point clouds will be further analyzed and used for localization and mapping of the environment.

3.1.40.2 360° Scanning Radar iSDR-C

A new and far smaller scanning radar has been developed. In Figure 3.102 a new prototype is shown. In comparison to the one shown in chapter 3, the sensor has a smaller antenna. The opening angle is $+/-4°$. The estimated maximal measurement distance is about 50m. Also fast moving objects can be measured. The rotation rate is specified with max. 25 rotations per second. *indurads* product name is iSDR-C (indurad scanning dynamic radar – compact). The current development state is a fully new designed housing. Internal, the radar technology is based on the same pcbs as in the large iSDR. With numerous patches, the radar is ready to use. Further work has to be done to finalize the pcb redesign and the design of the motor control unit.

The iSDR-C is planned to be mounted horizontally, this allows to detect not only all objects around the robot. It will also allow detecting the robots movements and rotations directly from distance measurements and changes. In comparison to

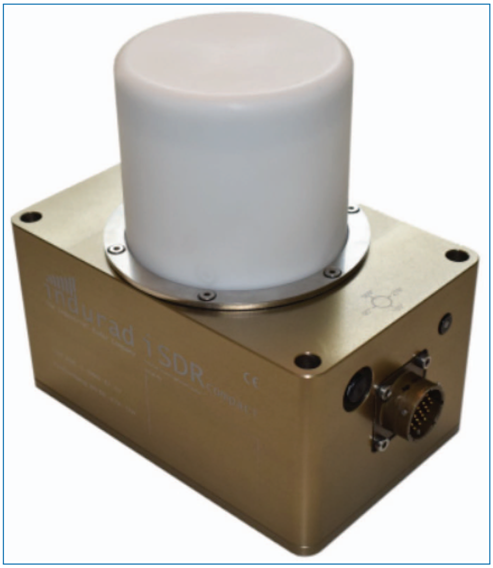


Figure 3.102. iSDR-C.

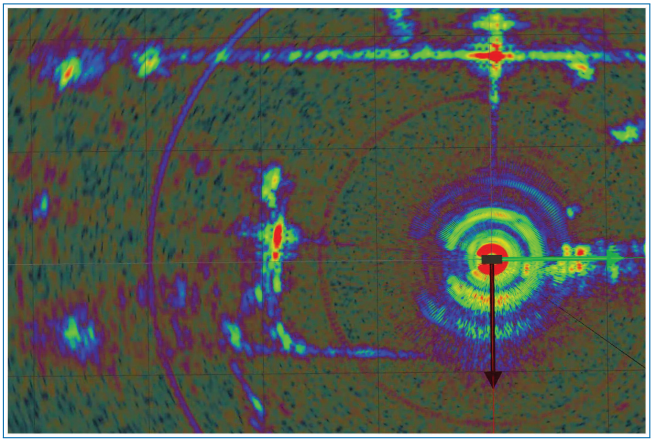


Figure 3.103. iSDR-C vertical scan with person.

speed measurements, e.g., with a Doppler radar there is no integration step required anymore. Even inertial motion data must not be used anymore. Detected accelerations must be integrated two times to calculate the movements.

Its principle operation was shown using one iSDR-C scanning a vertical plane. The iSDR-C was lying on a desk. The ceiling, floor and wall can be seen. In the middle left side a person walking through the measurement zone can be seen in Figure 3.103.

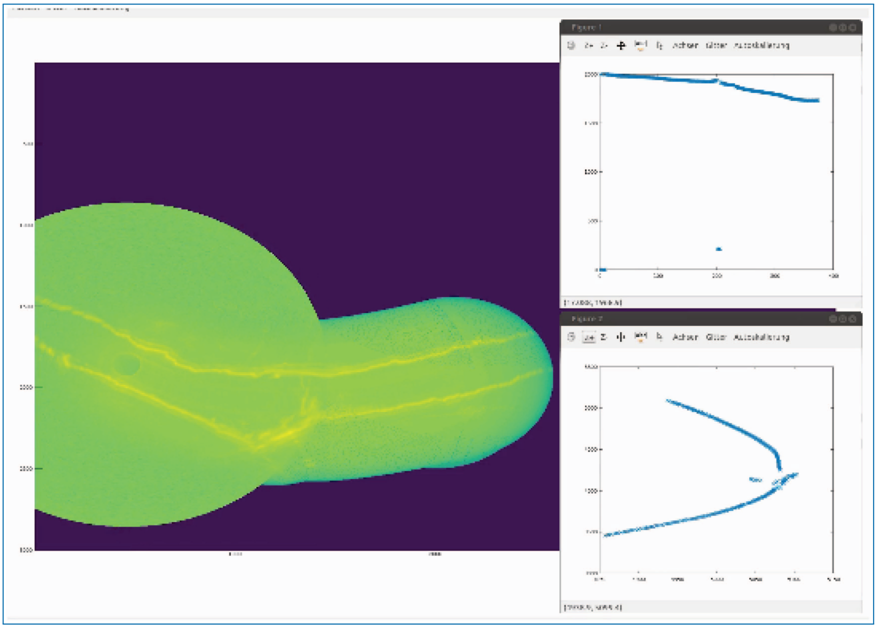


Figure 3.104. Reconstructed environment.

A first prove of concept was done, by reconstructing the surrounding fixed environment. The single 360° pictures of the radar are stitched together using 2D cross correlation. In Figure 3.104 such a picture is shown. The small graphs on the right show the detected angle with 2000 increments per 360° on the top, on the bottom a position is shown. (Please note the axes are scaled not equally). In Figure 14 it also can be seen that there has been obviously a wrong detection. There, the angle of the robots pose jumped to another angle and back. A complete system would use the radar data, the data of radio ranging and also the data measured by inertial measurement units. This will help to stabilize the stitching process and the speed detection.

3.1.40.3 Further Sensors

In addition to the previously mentioned sensors the LIDAR sensor technology used for the mobile platform (see Deliverable 4.1) is available for any non-dust situation. Furthermore the following sensors might be included in the future.

3.1.40.3.1 Inertial Sensor

As already stated in the subsection 4.2 additional acceleration sensors and gyroscopes might be used as additional sensor source to stabilize the UWB measurements. It allows evaluating the ranging information from measurement to measurement against the inertial sensor. Thus, invalid detection values can be identified more reliably and furthermore, using dead reckoning can be used during phases with poor ranging information. If applicable, the fusion of IMU measurements with exteroceptive sensors is in the scope of Task 6.2.

3.1.40.3.2 Lidar and 3D Camera

Lidar sensors and 3D cameras are also evaluated in Task 6.2. They might be used as initial measurement tools before grinding and maybe with a separate high precision environment sensing vehicle.

3.1.40.3.3 Automotive Radar

Typical automotive radar allows to measure distances on a 2D segment. A typical angular resolution is 2° with a distance resolution of 20cm. The horizontal opening angle is 16°, additionally there are near range areas with a reduced angular resolution of 4° and an opening angle of 50°.

The radar was primarily developed to detect other cars, e.g., for distance-keeping cruise control systems. More modern variants also allow break-assistance systems detecting objects as large as humans. The measurement rate is 10 to 15 measurements per second.

These radar types are optimized for environmental perception on a horizontal plane with comparably small required opening angles. To detect the surrounding of the robot a minimum of eight devices must be mounted, either on the robot or inside the room the robot shall work in.

In principle, the radars seem to be usable, however from experience *indurad* knows that in complicated multi-target situations the primary limit of the radars is the data rate of the CAN bus they are attached to. The bandwidth is limited, thus, only the targets with highest reflection value are transferred. This means dry wall materials like wood or drywalls hardly can be seen, but objects behind or inside them. Also, small objects might not be detected.

Limited distance resolution is another drawback. It is not easy to detect the position inside a room while moving. While standing still, statistical calculations on a number of measurements might allow sufficient position detections. In conclusion, the iSDR(-C) is preferable compared to automotive radar sensors.

3.1.41 Outlook and Future Work to be Carried Out

The basic sensor system has been developed successfully. Further work has to be done to analyze the camera system, including mounting positions, number of cameras and view angle. Also, motorized DOM cameras might be used in future to allow detailed analysis of grinded surfaces.

Since the last reporting period a major step has been done miniaturizing the iSDR. A functional prototype is now available.

The ultra-wide band system has shown to be able to detect the robots position and pose. Further work has to be conducted to verify its accuracy. First, the UWB measurement itself must be improved by taking the antenna delay into account. The antenna delay depends on the direction and on the mounting point at the robot. Therefore, calibration mechanisms have to be implemented.

The algorithms must be revised, such that all measurement results for all antenna units are used at one time and to deal with multipath effects. This gives the least square minimum optimized over all parameters. The unscented Kalman-Filter must be optimized to increase the output speed and minimize the deviation in case of single wrong measurements. Methods must be implemented to evaluate the validity of a single measurement. One of the preliminary findings is that it is better to skip possibly wrong measurements than to use them.

The whole localization system must be usable by the end-users of the asbestos removal robot. Thus, a simple method to setup the iRTT based localization system must be developed.

The final choice for a sensor system and thus the final improvements depend on the results of task 6.2, where the localization and mapping algorithms are developed. Therefore, the final adjustments of the sensors, both iRTT and iSDR, will be conducted in close cooperation with the participants of task 6.2.

3.1.42 Summary and Conclusion

Within Deliverable 4.2 a variety of sensors that can be used to detect the environment and the robots position and orientation have been analyzed. The sensors have been preselected on a nearby basis. The main criteria have been size and cost. Ultra-wide band localization is a promising cost effective solution. Cameras are required to help the operator, to document the grinding result and for users convenience. Inertial sensors can be jointly used together with other sensors. Mathematical methods like unscented Kalman filters can be used to track the robots position realizing the sensor fusion.

The work package 4.2 is not fully finished, as final design and development steps still need to be performed for some sensors. Further developments on the sensor systems are ongoing and will accompany the further developments of the prototypes. The functionality and accuracy of the UWB will be developed and analyzed further and the integration of the first functional iSDR prototype with interfaces to the robots is seen as a next major step to the completion of all systems.

A further main step is to implement a user interface to set up the UWB localization system conveniently. Ideally, this will be done using the iOAU based wireless user interface. With the touch screen the position of the anchor nodes mounted in the room shall be set in the embedded computer calculating the pose.

The delivery of this deliverable report was delayed due to the ongoing technical developments and the absence of some project members during the summer vacations. The delays are however not severe and the ongoing developments are continued, to ensure not to slow down the overall prototype development.

Deliverable 4.2 – Appendix
Control system of the mobile platform layout and ready for implementation

Authors: Dr. Matthias Rabel, Lucas Rohe, Robin Bernau, Martin Gritzan

3.1.43 Deliverable in the Context of the Work Program

Deliverable 4.2 has been completed since 2017-03-08. Within the related work package various sensors that can be used to measure the robot's position and orientation in the room have been introduced. One finding has been that the radio ranging system (iRTT) is not as precise as required to detect the accurate position. Thus, iRTT was not included in the second version of the asbestos removal robot. Instead the scanning radars are used to measure in 2D the surrounding environment. With simultaneous location and mapping algorithms the robot position can be detected exact.

During the second phase of Bots2Rec iRTT system was further analyzed and even modified to improve the system. The report covers this work.

3.1.44 Methods and Work Carried Out

This report is an appendix to Deliverable 4.2. The introduction of the radio ranging system (iRTT) which is mainly based on Ultra-Wide Band (UWB) communication is repeated for convenience and then extended with details to the hardware architecture and additional features not yet reported. A third communication system based on Phase Measurements that is embedded in the iRTT system is introduced and analyzed. Secondary a different ranging scheme based on time difference of arrival (TDOA) is introduced. Finally an improved multi-tag tracking method that uses inertial motion sensor data additional is introduced.

3.1.44.1 iRTT Hardware Platform

The following section 3.1 has been reported already in Deliverable 4.2.

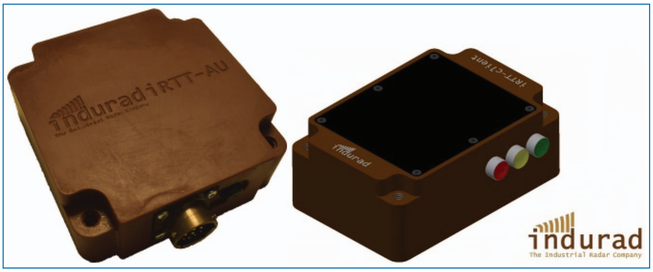


Figure 3.105. iRTT-AU and iRTT-CE.

3.1.44.2 Ultra-wide band-based location detection

Dependent on the used definitions ultra-wide band (UWB) communication operates with a signal bandwidth of >=50MHz or >=500MHz. Bandwidths between 50MHz and <500MHz are named as wide band (WB) systems, whereas ultra-wide band uses >= 500MHz as bandwidth.

The use of UWB radios is strongly limited to the intended use as described in the relevant European specifications (ETSI EN 302065). Indoor there are only power restrictions. Outdoor license free use is limited to handheld or vehicular.

UWB radios embed a fast running internal clock that is able to get timestamps on picosecond basis. Thus, the time of arrival of a message can be detected pretty exact. By exchanging data packets between the radio devices, the time of flight can be calculated. This process is called “two-way double-sided ranging”. With this the clock offset between the devices can be calculated. The clock skew causing errors can be minimized. Exact measurements rely on a direct line of sight and in best case multipath free environment. A theoretical distance accuracy of about 5cm seems to be possible with single measurement.

indurad has developed ranging devices using UWB. Two of them are iRTT-AU and iRTT-CE (Antenna Unit and Client Equipment). They have been developed for different purposes but are reused in a variation within the Bots2Rec project (Figure 3.105).

The technology is applied within very robust housings that can be used in underground mining. Thus, there is potential to reduce its size for the second, final robot prototype 2. The antenna units are mounted on the robot, the distance between any of the antenna units shall be maximized, also the mounting height must be variable to prevent symmetric axes or planes. E.g., if all four antenna units were mounted vertically along a line, then the system could not detect a direction, it could only detect the height and a radius. If all four antenna units ere mounted within one plane then the height would be ambiguous: either the solution is above or below the plane. A way to get rid of this ambiguity is to use context information. Inside a room the robot will most likely not change its height very much. Anyway, in case of more complex rooms, the height should be detectable.

Around the robot the 4 or more client equipment components are placed. They need to be fixed inside the room. These 4 devices can be used as anchor nodes. If the position of those four nodes is known every node on the robot can be localized using simple trigonometric functions.

The selected mathematical algorithm is taking in account, that the measurements might be wrong. Therefore, an approximation based algorithm like Gauss-Newton is used. An initial localization is used to start the algorithm. The output is generated after about 50 cycles.

The results of all four are measurements are again evaluated against the known mounting places of the antenna units on the robot. This allows matching the robots shape into the found positions. Finally, the robots pose is determined.

Additionally, an unscented Kalmannfilter implementation is used to track the position.

Figure 3.106 shows a row of pictures with different positions of the robot. Left, the calculated position is drawn. As additional information, the measured distances from any iRTT-CE to any iRTT-AU are drawn as circle around the anchor nodes (iRTT-CE). The large black dots are the iRTT-CE inside the room. The four colored dots are the iRTT-AU on the robot.

It can be seen that the shown positions fit to the photograph.

Additional in Figures 3.107 and 3.108 circles have been driven and the robot was moved forward and backward.

It can be seen that the measurements are repeatable. Nevertheless, the accuracy is just a rough estimation, since the robot could be hardly maneuvered in a circle with its remote control and also the algorithms are in an early stage.

Further work has to be conducted to improve the accuracy of the whole system. First the UWB measurement itself must be improved by taking the antenna delay into account. The antenna delay depends on the direction and on the mounting point at the robot. Therefore, calibration mechanisms have to be implemented.

The algorithms must be revised, such that all measurement results for all antenna units are used at one time. This gives the least square minimum optimized over all parameters.

The unscented Kalmanfilter must be optimized to increase the output speed and minimize the deviation in case of single wrong measurements. Methods must be implemented to evaluate the validity of a single measurement. One of the preliminary findings is, that it is better to skip possibly wrong measurements than to use them.

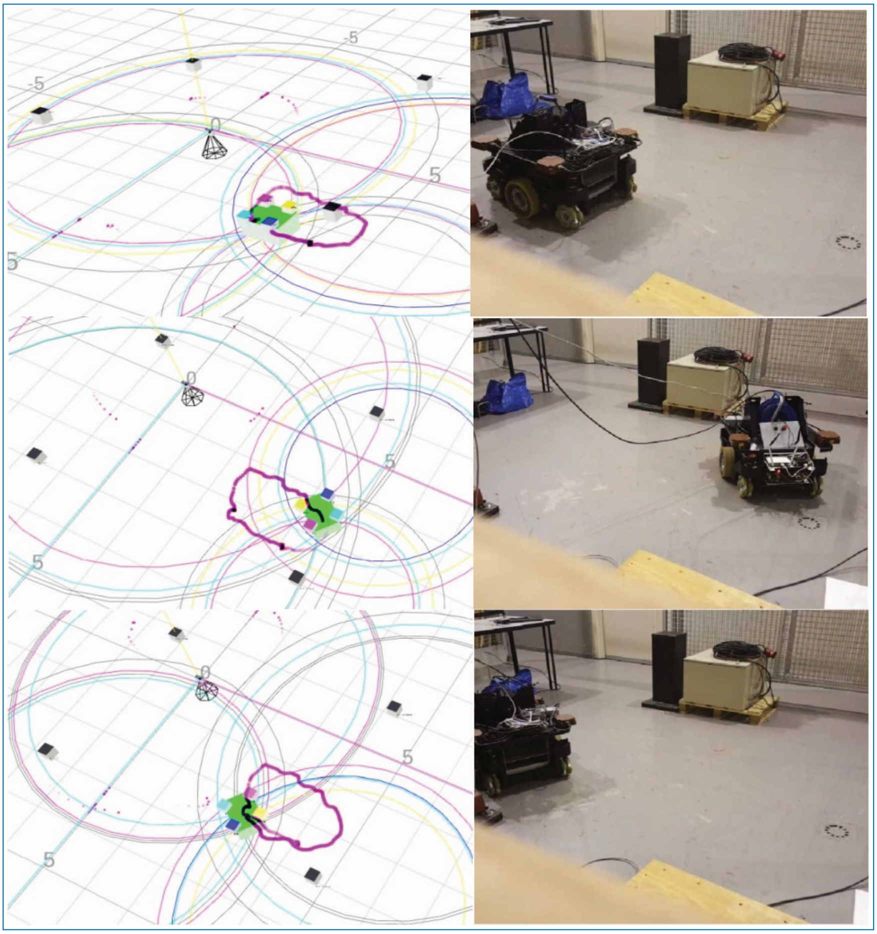


Figure 3.106. Robot position calculated / photograph.

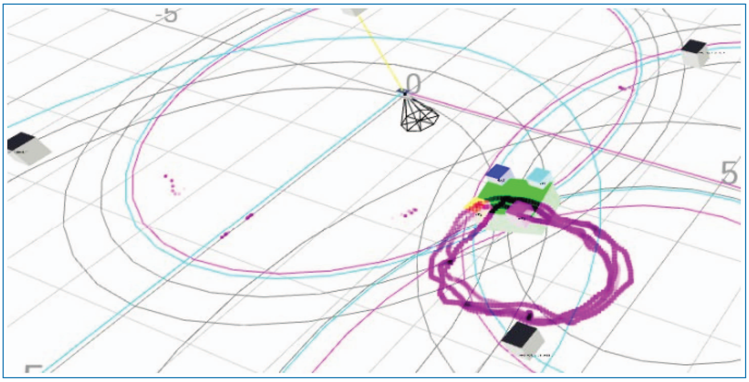


Figure 3.107. Repeatability: mobile platform driving circles.

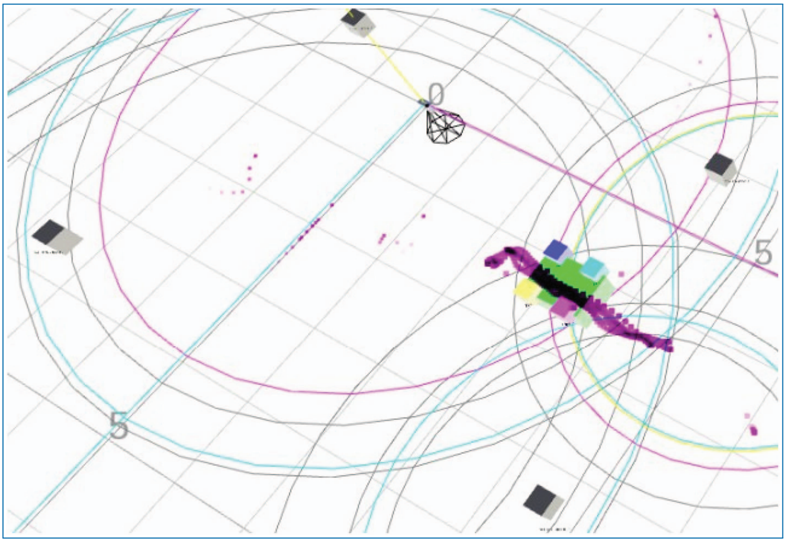


Figure 3.108. Repeatability: mobile platform driving for- and backward.

The whole localization system must be usable by the end-users of the asbestos removal robot. Thus a simple method to setup the iRTT based localization system must be developed.

3.1.44.3 Anchor System

The iRTT Hardware Platform is comprised of an indurad Radar Processing Unit (iRPU) and multiple different peripheral devices. The iRTT Antenna Units (iRTT-AU) are used as vehicular receivers. Their positions within the robot's geometry are known and form the ground truth for tracking calculations. Yet, Antenna Units can act as ranging anchors and tags alike which is further detailed within Section TODO. An iRTT-AU unites radio interfaces for the three different channels within one circuit board as shown in Figure 3.109.

One microcontroller (STM32) is used as the main processor of each Antenna Unit and serves multiple purposes. The UWB Ranging protocols are implemented within the main processor as it interfaces the Decawave DW1000 UWB radio frequency interface chip directly. The main processor computes distances for the time-of-flight (TOF) ranging scheme and forwards UWB timestamps required for accurate tracking via CAN bus towards the iRPU. Also, the main processor maintains configuration data accessible to the tracking logic through a specialized CAN-based protocol. Furthermore, it serves as a proxy for communication via the Sub-1 GHz radio.

The Sub-1 GHz channel is used for device presence detection and meta data communication between remote iRTT devices only. The robot's local iRPU can

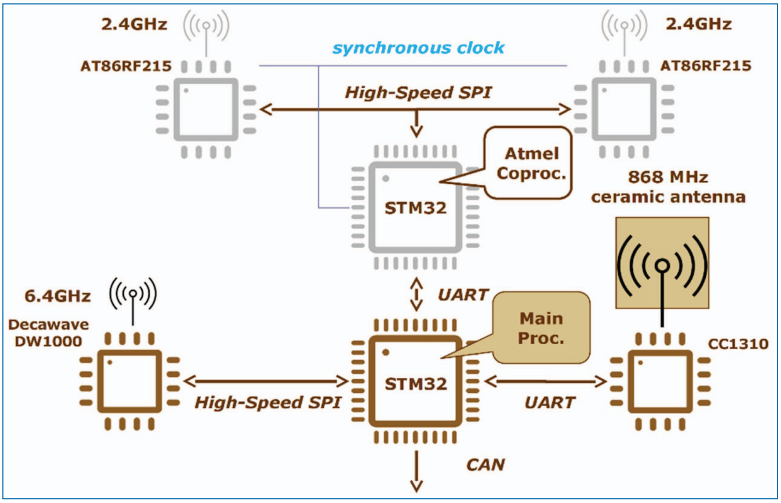


Figure 3.109. Sensor system layout, for mobile platform and robotic arm.

issue commands towards remote devices via the CAN bus which are forwarded through the main processor towards the dedicated coprocessor which broadcasts those messages towards all iRTT devices in the vicinity. A Texas Instruments CC1310 System-on-Chip is used for this purpose as it incorporates a user-programmable ARM-based processor alongside the actual radio interface.

The two ISM 2.4 GHz radio interface chips need strict timing requirements to be fulfilled for accurate measurement results, especially for the antenna diversity measurement scenario. A second STM32 is introduced as the dedicated ISM coprocessor. It services a specialized SPI interface towards the two radio interface chips to achieve the timing requirements. A serial connection to the main processor is maintained to exchange commands and results.

3.1.44.4 Inertial Sensor Extension

As stated in the report Deliverable 4.2 in the subchapter 3.1, a 6-axis inertial measurement unit has been connected to the extension interface of the radio ranging anchor hardware.

The additional acceleration sensors and gyroscopes are used as additional sensor source to stylize the UWB measurements. It allows evaluating the ranging information from measurement to measurement against the inertial sensor. Thus, invalid detection values can be detected more reliably and further more using dead reckoning can be used during phases with poor ranging information. Chapter 5 describes an experiment with a combined setup that uses UWB and the acceleration sensors.

3.1.44.5 Tag System

The iRTT Client devices serve as ranging tags of known position within the robot's working area. Much like the Antenna Unit the client unites all three radio interfaces on one PCB, however, with focus on the comparably smaller size and power consumption required for operation independent of mains supply and without hard-wired connection to any supervising iRPU. The structure is shown in Figure 3.110.

Within the client the same Texas Instruments CC1310 also applied as the iRTT-AU's Sub-1 GHz coprocessor is used as the main processing unit which interfaces all RF chips directly.

For UWB the Client only serves as a Tag and does not compute any results. Hence, the required logic is much simpler compared to the Antenna Unit's implementation. Same holds true for the ISM ranging where only a single radio interface is applied for the sake of both device size and battery life. This also reduces the timing requirements' strictness compared to the Antenna Unit allowing the Client to serve both RF chips through the same serial interface.

An inertial measurement unit is introduced for orientation detection on the Client devices. The orientation information can be used to optimize tracking based on the known antenna geometry.

3.1.44.6 Time of Flight (TOF)

The so called Three-Way-ToF method visualized in Figure 3.111 enables measurements of distances between transponder tags and stationary reference anchors. For each distance measurement three data packets are exchanged: (1) tag → anchor, (2) anchor → tag, (3) tag → anchor.

This results in six timestamps which can be used to determine the signal propagation delay between the tag-and anchor pair. Using the speed of light, the delay values can be converted into distance information. This method does not require

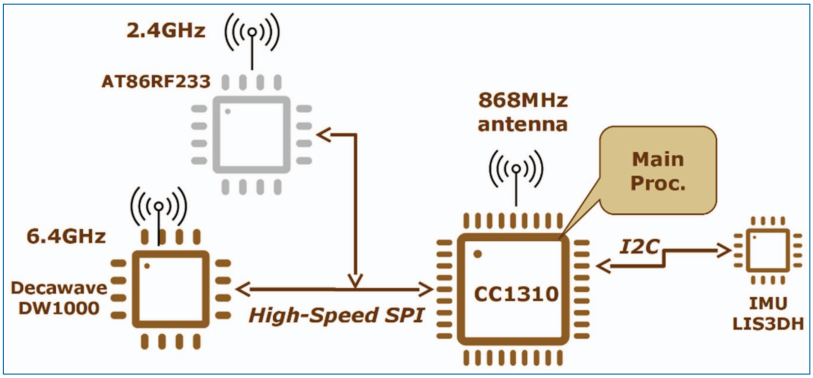


Figure 3.110. Signal and control flow.

the clocks of the devices to be synchronized. Anyway, the assumption is that the clocks are running stable. In fact, the phase noise which is in principal an inherent part of any clock source is a major source of errors.

The graphical representation of a single ToF in 3D space is a sphere with radius r = distance and center position p = position of the anchor. For the positioning of a tag in that 3D space at least four ToF measurements from different anchors are required in order to get an unambiguous point of intersection. In Figure 8 three small circles and some more large circles can be seen. The blue cube is drawn at the point where all circles have their intersection. In static measurement situations the result is very stable.

In case the tag moves, the distances between multiple anchors and one tag must be acquired within short time. This is achieved by an optimized channel access algorithm. Anyway, the sequence of measurements dependent on the tag speed will always lead to an error. Robust tracking algorithms must be deployed.

The initiating handshake packet is transmitted by the tag as a broadcast message. Each anchor is assigned a time slot to respond within when it receives such. For each responding anchor the tag stores response timestamp information and publishes all these in the final message of the handshake. This scheme enables up to 24 anchors

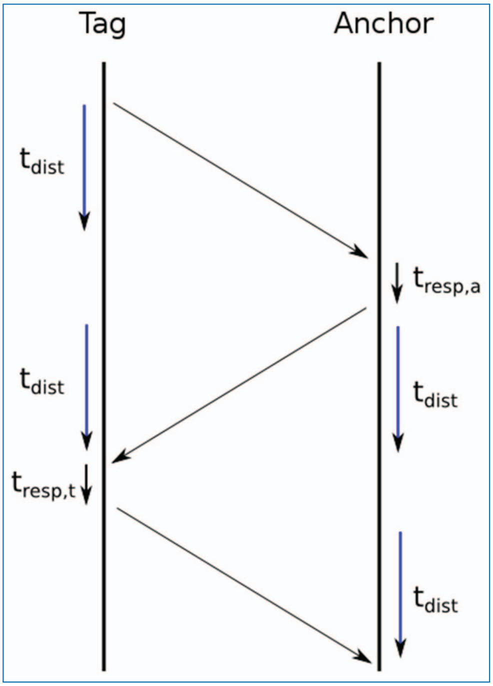


Figure 3.111. Time-of-Flight (ToF) Three Way Ranging.

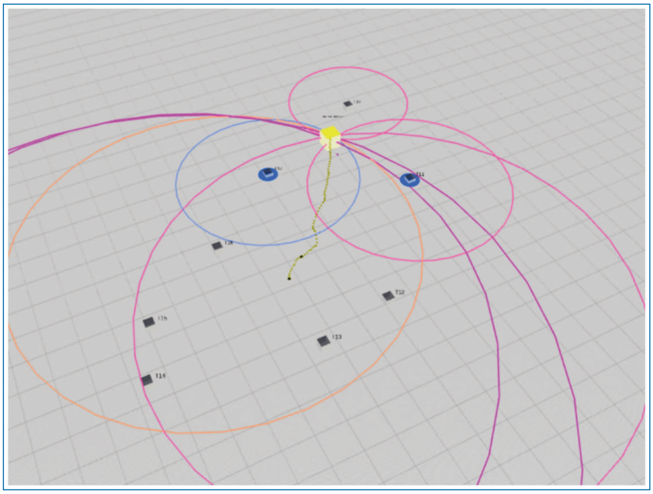


Figure 3.112. Visualization of Time of Flight (ToF) as distance circles between anchors and tag (blue block).

to measure distance to a single tag within one set of handshakes, taking only about 30 ms of air time.

Especially the ToF measurements rely on the radio interface chip to accurately measure the frames' timestamps. These measurements can, however, be impaired by radio frequency packet collisions. Such collisions must be avoided as much as possible. The probability of a collision occurring is reduced by means of configuring the anchors to each respond in a different time slot and by the tags modifying their handshake initiation period at random. These two precautions are found to contribute largely to the quality of ToF measurement results.

3.1.44.7 Time Difference of Arrival (TDoA)

The second method, TDoA, is based on differences of the propagation delay between the tag and a number of different anchors. The tag sends out broadcasts which are received by the anchors at different points in time (Time of Arrival, ToA). As long as the clocks of the anchors are synchronized the differences of the receive timestamps (Time Difference of Arrival, TDoA) can be determined. Due to the speed of propagation (speed of light) of the electromagnetic waves this method demands an error in synchronization smaller than a nanosecond.

The synchronization is based on dedicated data packets (Time of Send and Arrival, ToSA) that are sent out via radio waves from the synchronization reference anchors with a sufficiently high rate of 3 Hz. This way a time delay and drift of the clocks can be calculated and the clocks of the different anchors can be translated into a global time system.

Alternatively, the reference clocks for all UWB radio interfaces can be driven from a single clock source. Additionally, a synchronization pulse can be distributed among all devices to reset their timestamp counters to zero at about the same time. A small inaccuracy is still introduced by the different electrical lengths between the central clock distribution and the individual devices and has to be calibrated out during the subsequent tracking algorithm.

A TDoA measurement can be represented as a 3D hyperbola whose inflection point lies in between the receiving anchors and corresponds to the tag position. For the positioning in 3D space at least five hyperbolas are required.

The iRTT system uses both methods in order to compensate the disadvantages of each method with the advantages of the other: The ToF method does not scale well with many participants (transponder tags). A measurement of one tag with 24 anchors lasts approximately 20 ms during which time no other tag can initiate a measurement. The advantage is the direct result which is consistent and does not need an additional complex processing afterwards.

For the TDoA method the clocks need to be actively synchronized and two timestamps are necessary to obtain one TDoA measurement. The processing and the underlying communication protocol are more complex. The key advantage of the TDoA method is the scalability. A TDoA broadcast takes less than 1 ms can be received from many anchors at the same time. This enables setups with a large number of anchors and tags.

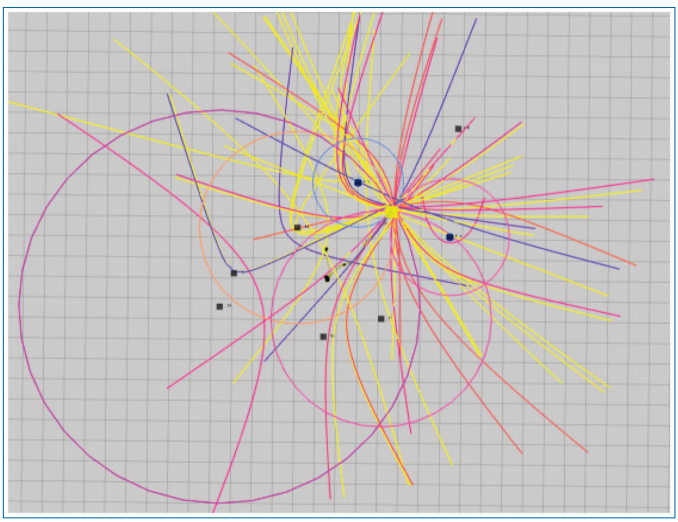


Figure 3.113. Visualization of TDoA measurements (hyperbolas) and ToF measurements (circles).

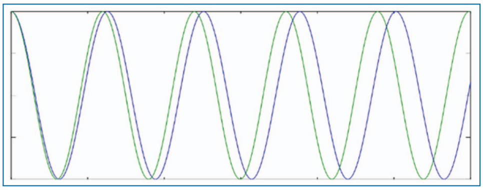


Figure 3.114. Small frequency differences lead to a changed phase position in the receiver.

3.1.45 Phase Measurement System

This ranging system operates within the 2.4 GHz ISM (industrial scientific medical) band. The IEEE 802.15.4 channel 26 at 2.48 GHz is used for negotiation purposes with QPSK modulation scheme while the actual ranging uses a frequency sweep across the whole ISM band from 2.405–2.483 GHz.

3.1.45.1 Phase Measurement Method

A phase measurement unit (PMU) in the radio chips measuring phase angle on constant frequencies. An equal spaced number of frequencies are stepped through and the differences are calculated and averaged. The resulting value is a measure for the distance. At a given distance the multiple of wavelengths filling up that distance is different across frequencies. The ambiguity can be resolved measuring round trip times in the communication. Typical at a round 120m the phase angle roles over the first time. Figure 10 visualizes this effect. The horizontal axis is the distance, the vertical axis is the phase angle. When the sender is on the far-left and the receiver is on the far-right position of the graph, the receiver will detect a different phase angle for slightly different frequencies.

Under ideal conditions plotting phase over an equidistant set of frequencies yields a straight line where the slope directly corresponds to the distance.

3.1.45.2 PMU Ranging Scheme

The ranging is initiated by an anchor sending a range request to any tag using a standard IEEE 802.15.4 frame. A short negotiation period follows where tag and anchor agree on a set of frequencies to use for the ranging. Then follows a phase where both tag and anchor synchronously step through this set of frequencies. At each frequency the tag transmits a sine wave for a short period while the anchor measures the received signal's phase relative to its internal generator along with other parameters such as signal strength. Next, tag and anchor switch roles, with the anchor transmitting the sine and the tag measuring before commencing to the next frequency.

After finishing this phase measurement set the tag transmits its measurements back to the anchor, again using standard IEEE frames. The anchor is able to compute a distance from these and its own data.

The double-sided process is necessary because in practice it is not directly possible to measure the arriving signal's phase relative to the transmitter but only to the receiver's internal reference. The divergence between the two are calibrated out by comparing the phase samples of the same frequency across both tag and anchor receivers.

In practice, non-line-of-sight conditions, timing inaccuracy and external disturbance results in the phase samples not forming a straight but rather, a point cloud. To still obtain the distance a straight is subsequently fitted through the point cloud and outliers are eliminated.

3.1.45.3 PMU Ranging with Antenna Diversity

The iRTT Antenna Unit incorporates two separate interface chips which are clocked synchronously. This allows to use passive antenna diversity to overcome further disturbances.

Only a single RF chip is used for communication with the remote device in both tag and anchor mode. During the local device's receiving turn of the frequency stepping procedure the second chip's phase measurement unit is synchronously sampled, yielding an additional frequency-phase point to the point cloud.

This method ensures that the ranging scheme itself does not need to be altered compared to the single-receiver case and allows both iRTT clients with only one interface and Antenna Units with two interfaces to act as ranging targets within the scheme.

3.1.45.4 PMU Ranging Experimental Setup

In order to evaluate the accuracy and the reliability of the newly developed distance measurement system based on radio phase differences in the 2,4 GHz ISM band, two kinds of experiments were carried out on the V2 Robot at the IGMR in Aachen:

Straight traversal of the robot front first and rear first in a constant speed towards an iRTT-CP-Tag. Distance measurements with from all AU's to the tag with 1Hz rate.

Rotation of the robot basis on in front of an iRTT-CP-Tag with constant angular rate and fixed distance towards the CP-Tag. Distance measurements with from all AU's to the tag with 1Hz rate.

Both experiments were conducted inside the IGMR-laboratory with the back part of the V2 Robot, which was steered manually with a wireless gamepad. The

Figure 3.115. Mounting positions and orientation of iRTT-AUs and CP-Tag.

iRTT measurement system consisted of four sideward facing and one upwards facing iRTT-AU-V2, mounted on a wooden board which was fixated on top of the robot and in parallel to its basis as shown in Figure 3.110.

Figure 3.115: Mounting positions and orientation of iRTT-AUs and CP-Tag shows the schematic setup of the iRTT measurement system on top of the board. The four iRTT-AU's S0A1 S1A1, S2A1 and S3A1 were mounted at each corner of the board with their backs facing to the center. The S4A1 was also used as a

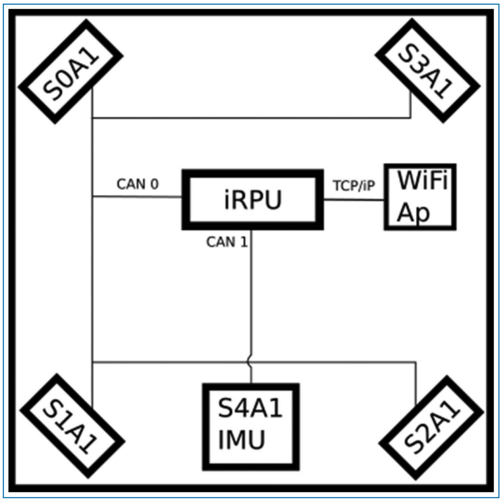


Figure 3.116. Schematic setup.

reference anchor for TDoA measurements and provided additional inertial sensor data. Therefore, it was mounted facing upwards to simplify yaw-angular rate measurements.

Distance measurement streams were provided via indurads proprietary stream protocol based on one shared high-speed CAN-bus connection to a central processing unit called IRPU. Due to significantly higher sample rates for the IMU measurements, a second CAN bus was established for S4A1 to reduce bus utilization.

3.1.45.5 Result and Discussion

Figure 3.112 shows the distance measurements from tag b6d43d to all installed AU's based on the technologies UWB Time-of-Arrival (UWB ToF) and phase differentials (PMU).

The graph depicts the straight traversal of the robot starting at 1 m distance towards the 7 m mark (distance to front facing AU's) and back again

It is clearly visible that the improved UWB-ToF ranging outperform the newly developed PMU based ranging both in accuracy and reliability. While there is a visible distance trend especially for the front facing two AU's S0A1 and S3A1, the measurement scatter of the other three averted AU's is too severe to be used in any positioning algorithm.

Even though the 2,4 Ghz ISM band allows for a higher output power of about 20dBm compared to UWB with -14dBm and its longer wavelength should provide easier NLOS detections, there is currently no reliable measurement quality indicator offered from the PMU chip to reliably detect multi path measurements and the overall error variance of the system is too high.

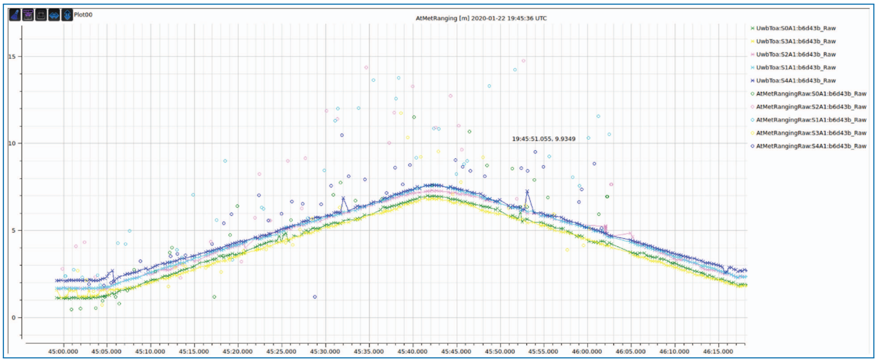


Figure 3.117. Front facing straight traversal all AU's.

However, the signal processing chain of the PMU system might be further improved with appropriate signal filters. Furthermore, the system might be used as an occasional support to resolve positioning ambiguities of the UWB ToF-system.

3.1.46 Multitag Tracking

The pose tracking system is based on a set of indurad iRTT-AUs (M) which get installed onto the robot (p_M) and a set of iRTT-CE tags (N) which are installed in the working area and get measured in accurately in the rooms coordinate system (p_N). Additionally, an inertial measurement unit is used for tracking movement dynamics.

The following sequence describes the main steps realized to get the robots pose. Figure 3.118 show this graphical:

- The tags periodically initiate distance measurements (d_{MN}) with all anchors installed on the robot. This resulting set of distances is used for estimating the rooms pose R (x,y,z, roll, pitch, yaw) relative to the robot (or vice versa). With corresponding object function of form:

$$f\,(R) = min_R \left\{ \sum_{MN} ||p_M - R * p_N||_2 - d_{MN} \right\}.$$

- Simultaneously the tags emit broadcasts which get received by the robot's anchors. Since the anchor clocks get synchronized via air, a TDoA (Time Difference of Arrival) can be deduced. Using the speed of light, the TDoA can be converted into a distance difference of arrival (DDoA). For pairs of receiving anchors at position p_{aM} and p_{bM}we can estimate the tags pose R using the object function:

$$f(R) = min_R \left\{ \sum_{(MxM)N} (||p_{aM} - R * p_N||_2 - ||p_{bM} - R * p_N||_2) - DDoA_{abMN} \right\}$$

- We combine samples of both measurement methods in a common Unscented Kalman Tracker state. During the update step, either objective function is used for comparing the data set with the Kalman trackers state.
- Measurements with a higher probability of being NLOS are down-weighted by applying a higher measurement noise to them. Additionally, we reduce the Kalman Trackers innovation by down-weighting measurements which deviate too much from the current state (Robust Kalman).
- A Madgwick filter is used for combining and integrating the inertial measurements units (IMU) accelerator and gyroscope measurements to an absolute orientation of the robot. We duce orientation changes from the filters result and apply those to the Kalman trackers state as control input.

3.1.46.1 Multitag Tracking Results

The most recent robot setup was tested during a trail at IGMR institute. A set of six iRTT-Tags got installed at the rooms edges and a two reference squares (1 m x 1 m, 3 m x 3 m) were measured in accurately relative to the rooms local coordinate system.

The system was configured to conduct ToF/TDoA measurements with a sample rate of 3 Hz and IMU measurements with 100 Hz.

During pre-tests the TDoA subsystem has been evaluated. Even though the synchronization is functional and stable, the provided accuracy is not sufficient for a narrow anchor configuration.

The system is subject to a typical synchronization error of ten Decawave time units which leads to a TDoA measuring error of approx. 10 cm.

The systems pose estimation proved to be reliable in the chosen measurement configuration. The maximal position error was approx. 20 cm from the reference position and orientation estimation was stable thorough the trail showing a maximal orientation estimation error of approx. 20°.

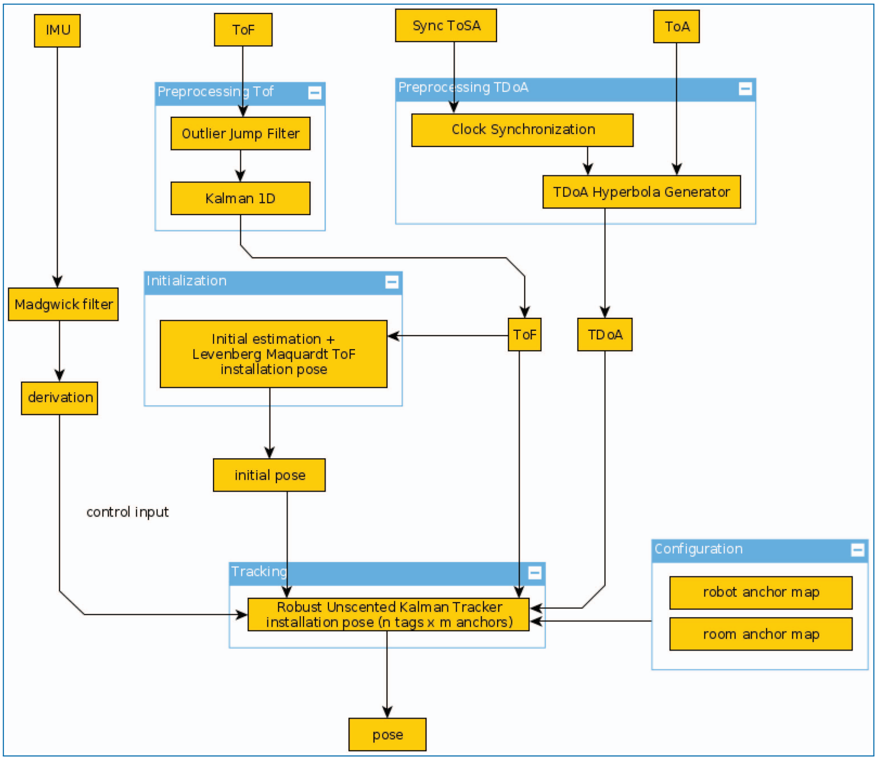


Figure 3.118. Tracking: data flow and algorithms.

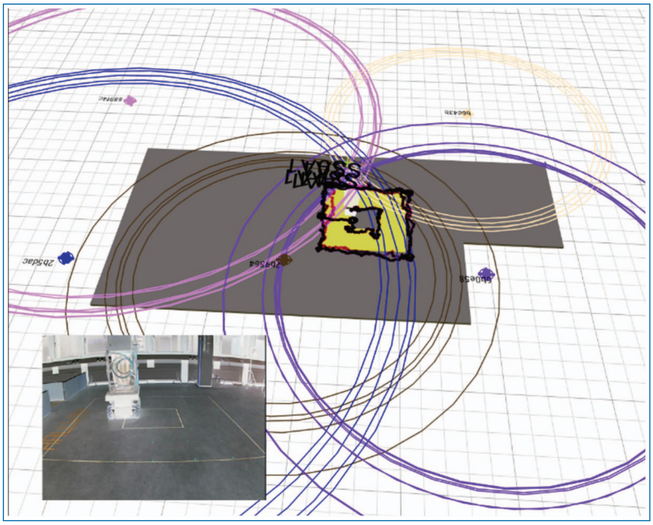


Figure 3.119. Pose Tracking: estimated trajectory (black path) and corresponding distance measurement circles.

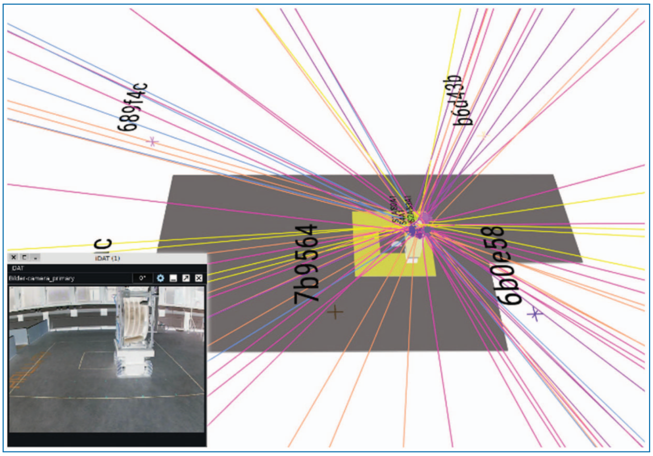


Figure 3.120. TDOA: measured TDoA visualized in plane z=2 m. Sending iRTT tag id is encoded as hyperbola color.

3.1.47 Summary and Conclusion

In this Appendix to Deliverable 4.2 we have elaborated different possibilities to improve radio ranging accuracy. A phase measurement scheme at 2,4GHz has been analyzed and tried. Far too high measurement deviations and also a rather slow measurement system that limits its practical use to static systems must be reported. Thus, the system will not be followed up further.

Another trial with over the air synchronized UWB anchors shows a far more stable location detection compared to the results in Deliverable 4.2. The UWB measurements further have been stabilized with acceleration measurements from a 6-axis inertial motion sensor. These results are promising, the combined TDOA an IMU system will be improved in future, with hard wired synchronization lines removing the different anchors clock jitter almost entirely.

Deliverable D5.3
Sensor System for local process monitoring implemented and functional

Authors: Dr. Matthias Rabel

3.1.48 Deliverable in the Context of the Work Program

Scanning the surface before, during and after treatment is a key technique for optimized work processes. Before treatment, the work area is scanned as reference and to optimally assist the user who makes the selection. During processing, the area is monitored to document the progress. Events like sudden spalling of large areas, or the detection of disturbing objects shall be detected to optimize the work process during the treatment. Visual process monitoring by camera might possibly not be usable during the treatment due to the amount of dust generated and will be supported by radar technique to overcome this issue. Similar to deliverable 4.2 the same camera system is preliminary used on the prototype 1 of the asbestos removal robot.

3.1.49 Methods and Work Carried Out

The asbestos removal robot is moved using the mobile platform. It is placed in front of a wall or other surfaces where grinding has to be done. The grinding disc can then be used to operate on a selected region of the surface. Since the robot can never be placed with an accuracy of a few millimeters and the mechanics has also tolerances, a measurement system is required to detect the actual geometric situation. This is required to allow a controlled grinding process. The grinding disc must be oriented exactly parallel to the surface at any time. Thus, a measurement system is required that is insensitive against dust.

Several systems are discussed:

- A radar based system that can be used on multiple positions around the disc to measure the distance to the wall.
- The second sensor is a force measuring component placed in between the robot's arm and the robot's grinding machine. Linear and rotational forces are measured with this device with strain gauges. There is no experience yet with the force feedback sensor, it is currently replaced by a dummy component.
- The third system, a camera based system, shall only be used to check the grinding results. It is implemented and functional, however, the real usage is still under development.

The radar based system has been developed from scratch during the first project year. Its concept is described in the further chapters.

3.1.50 Sensor System for Local Process Monitoring

Figure 3.123 shows the general layout of the sensor system implemented on the asbestos removal robot prototype 1. Within the dashed area, the mobile platform is shown. The manipulator arm is mounted on the robot platform. Up to 5 iLDR120 "indurad linear dynamic radar" shall be mounted around the grinding disc. Additionally, two cameras might be placed on the robot to evaluate the grinding result.

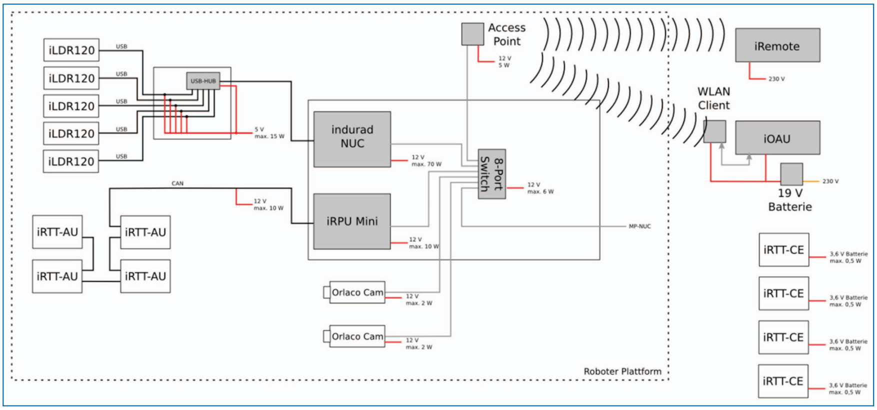


Figure 3.121. Sensor system layout, for mobile platform and robotic arm.

Figure 3.122. Orlaco camera EMOS Ethernet; Example picture underground.

Several other components are shown. These are used on the mobile platform. The sensor system is further described in Deliverable 4.2. The shown indurad NUC intel computer is used to connect the radars with USB 2.0. The data is processed and the results can be fetched via the graphical user interface iOAU (indurad operator assistant unit) or the robot control processing unit. The iOAU is also used to calibrate the sensors.

3.1.50.1 Camera System

The camera system is used to give the operator an environmental view and shall be used to check the process result of grinding. The work conducted in deliverable 5.2 focuses on monitoring the process results. Within deliverable 4.2, the focus is on the environmental view using the same cameras.

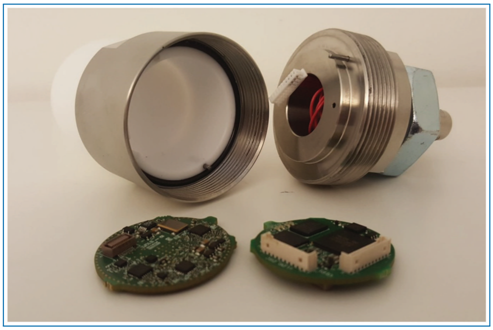


Figure 3.123. iLDR120 with FE (left) and DSC (right) board.

The cameras are available with 120° and 180° opening angle. Variants with 90°, 60° and 30° are planned by the manufacturer. The camera allows a video resolution of up to 960p with 45 frames per second. The housing is IP68 and IP69k specified. Thus, it can easily be used in dusty environments.

The camera has a high dynamic range of > 115dB and has a low light feature. Figure 3.122 shows the camera and a picture taken underground with a 120° variant. The picture quality is quite good. The only areas exceeding the dynamic range are the dark corners of the image and at the light bulbs.

The full usage and functionality will be evaluated with the first real grinding tests including the operational GUI. The concept will be revised after the first results.

3.1.50.2 1D Radar System

To be able to measure the distance from the tool to the processed wall, five iLDR120 sensors should be mounted next to the cutter tool. The requirements are as follows:

- Small package dimensions
- Light weight
- Dust resistant
- Easy to mount on the arm
- Only one cable for power supply and data transmission
- A small beam width in the antenna diagram

By using a highly integrated 120 GHz radar chip, the dimensions of the sensor can be minimized. This chip offers a bandwidth of up to 7 GHz from 119 GHz to 126 GHz. This allows operation in the so-called industrial, scientific and medical frequency band (ISM) that starts from 121GHz and ends at 122 GHz. The silicon-germanium based chip includes mixer, power amplifier, two patch antenna arrays for transmitting and receiving, low-noise amplifier and IQ down converter.

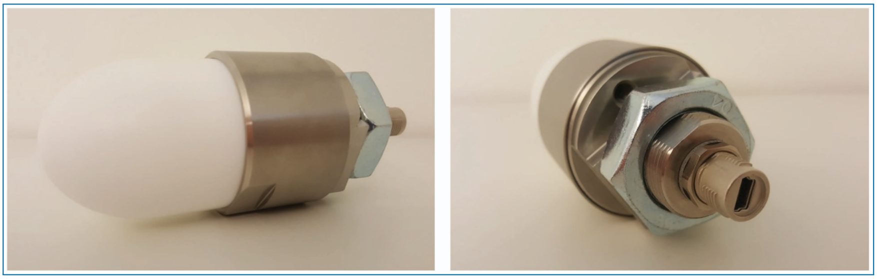


Figure 3.124. iLDR120 sensor housing.

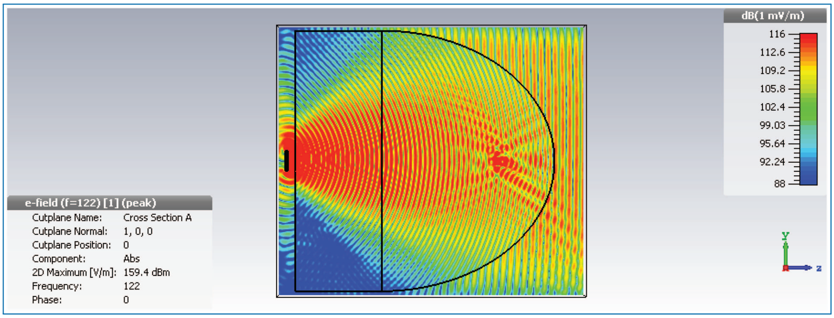


Figure 3.125. Simulation model and electric field magnitude [dBm].

Two printed circuit boards (PCB) have been designed and manufactured as depicted in Figure 3.123. The frontend (FE) circuit contains all components for frequency generation including the phase-looked-loop (PLL). The reference signal is generated by a programmable PLL. In the receiving path, multiple amplifiers and filters prepare the signal for the analog-digital conversion on the digital signal controller (DSC) circuit. On this second PCB, which is directly connected to the frontend circuit, the DSC is used to process the received signal. The 512k x 16 bit SRAM allows the storage of several radar measurements before transmitting the data via a serial USB interface. This USB interface is used as power supply of the sensor as well.

The sensor casing in Figure 3.124 consists of a PTFE lens and a stainless steel body. To mount the sensor on the arm easily, a thread has been integrated at the lower end. There is only one M24 nut required to fix the sensor. A Mini-USB-M12 connector ensures a dust-resistive connection of the sensor.

The DSC and FE circuit will be placed into the lens, which has been developed to narrow the beam width of the chip antennas. For the present application, a beam-width of $+/-25°$ is not sufficient and has been improved to $+/-1.8°$. The lens has been constructed with a microwave simulation tool and converts a spherical wave into a plane wave. An antenna gain of 32 dBi has been reached. The simulation model and the electric field magnitude can be seen in Figure 3.125.

Currently, the sensor is not yet fully functional. The software is still under development. Several tests on the first PCBs have shown several issues that have to be improved. The overall power consumption must be optimized. Continuously the radar consumes about 3.5W. This is far too much to be usable embedded inside of a Teflon lens. Thus the concept is further developed to embed a heat guiding system. The heat will then be transferred to the steel parts of the housing.

Also the electronics will be revised to shrink power consumption. The goal is a maximum power consumption of 2.5W. This equals a standard USB port that provides 500mA at 5V supply voltage.

3.1.51 Realization

During the project three design cycles have been completed. The PCB (printed circuit design) has been improved to solve production related issues. Also the design has been improved to reduce the power requirements. Till end of June 2018 we have received Version 3 of the sensors.

- Version 1: has only partly been working, we could only test basic functions and static radar functions that did not allow a distance measurement.
- Version 2: this version has been working. The radar has been tested and has been installed at Bots2Rec Prototype Number 1. The following subchapters are summarizing the results.
- Version 3: Now of writing this document only a first evaluation has been done. The radar has been working out of the box. New power management features are working in principle. During the measurement 500mA as current is drawn, turning off all radar related components the current is 250mA. Dependent on the amount of calculations and the measurement rate. The DSP might also be powered down partly, thus further power saving is possible. The design additional has a strongly improved design to reduce thermal resistances. That allows an easier thermal flow towards the 1D-radar mount.

3.1.51.1 Radar Tests

One of the first tests have been distance tests. Therefore, a linear axis with a stepping motor has been used to move a reflector in front of the radar. The distance of the maximum signal peak has been evaluated. Since the linear axis is moving with a constant speed, any measurement is ideally on a linear line. The following plot shows a distance in [m] on the vertical axis, on the horizontal axis the measurement number. The measurements up to now might jitter several milliseconds. In future firmware versions, using an already existing hardware timer will solve this issue. The speed has been 12,5mm/s.

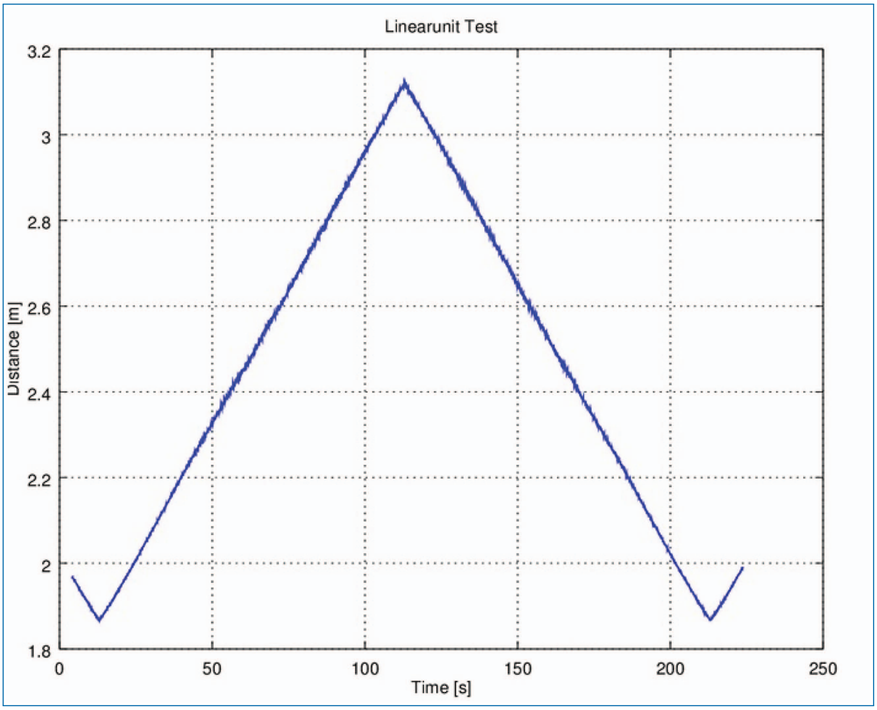


Figure 3.126. Linear Axis Test, Overview.

Differentiating the graph the result should show a horizontal line with a positive or negative offset. The following picture shows the result. The measurement rate has been 25 samples per second. The averaging length is 20 measurements. This results in 10mm steps in the following graph.

Obviously, the measurements are not yet linear and there is measurement noise. The following picture shows the samples 500 to 2000 more in detail. The deviation is +/-1,5mm over the length of 1,2m.

One main reason causing noise is the programming of the radar chip and the AD convertor. In Board revision V2R1 the operation is non-coherent. The second reason is that the reflecting target has been a trihedral reflector. It should be a sphere instead, as it is a point reflector. Another source of error is the measurement quite near to the linear axis, thus multipath will influence the measurement slightly. The direct and the multipath are causing targets close to each other. Due to the minimal distance, those two peaks cannot be separated.

During discussion of the results we have found, that the PCBs in the mounting fixtures are not entirely fixed. Thus as the linear axis is using a stepper motor and the steps cause a stuttering movement, including that the mounting fixture is not completely stiff, the dynamic movements and vibrations cause as well a noisy result.

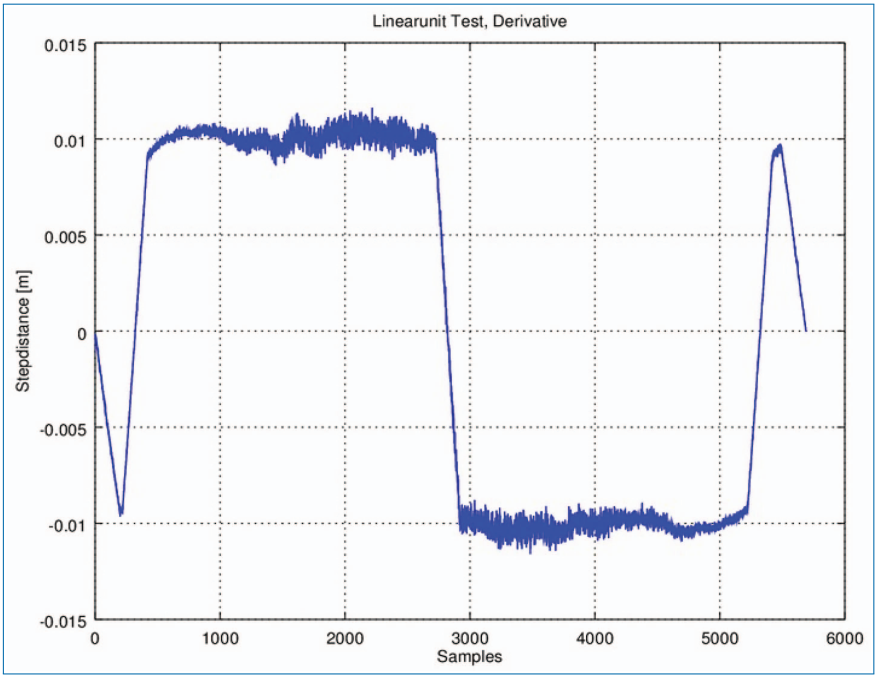


Figure 3.127. Difference from measurement to measurement.

Another experiment that should give us an idea of the effective antenna diagram has shown, that there is some deviation of the maximum peak in the antenna diagram that should be perfectly aligned. The deviation is $-2{,}1^\circ$ around the view axis, and 7.6° to the side. the This error was expected, but could not be simulated in advance, as we do not have enough detailed knowledge of the materials used in the radar chip. Since the transmitting and receiving antennas are separated there are two antenna diagrams. We need to find the point behind the lens, with the resulting maximum peak along the axis of the antenna. This only can be realized in experiments.

3.1.51.2 Installation on the handling arm on Prototype 1

4 of the radars are installed on the asbestos robot prototype V1. The integration has been realized using USB cables that are connected to a USB hub, which provides every radar the supply voltage of 5V and maximum current of 500mA. The USB hub is connected to an embedded computer, the NUC PC on the robot. The software executed on the NUC PC receives the raw data, calculates the FFT and searches the maximum peak in configurable distance limits. The following pictures shows the mount.

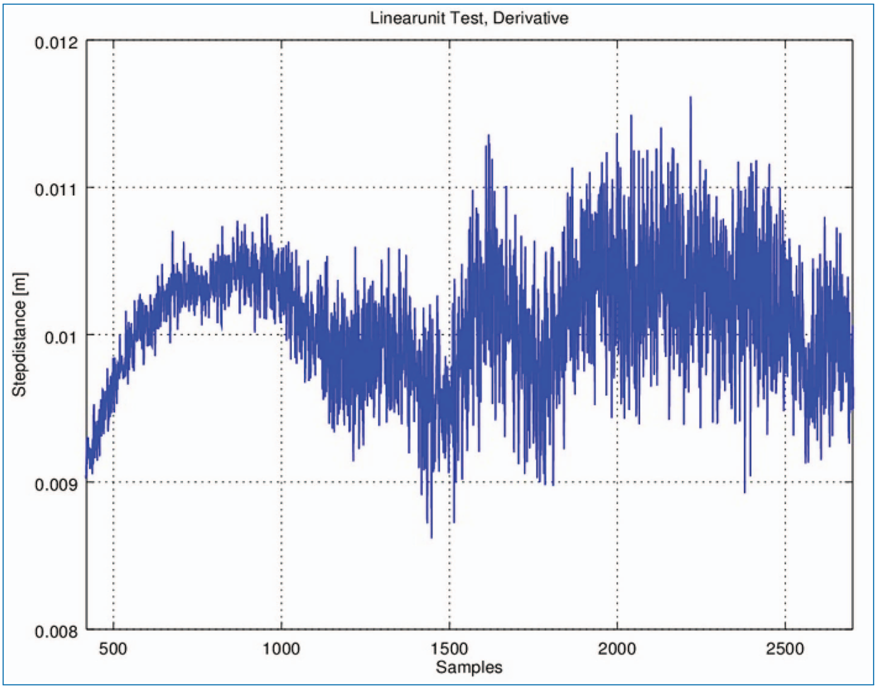


Figure 3.128. Zoom of sample 500 to 2000.

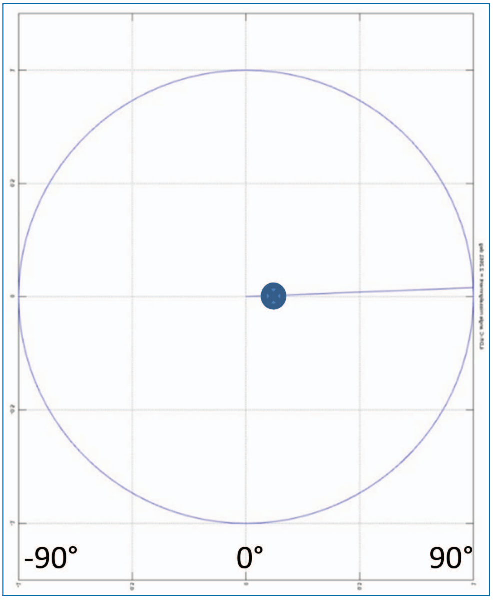


Figure 3.129. Orientation of the chip and deviation of the maximum peak.

Figure 3.130. 1D radar mounting fixture.

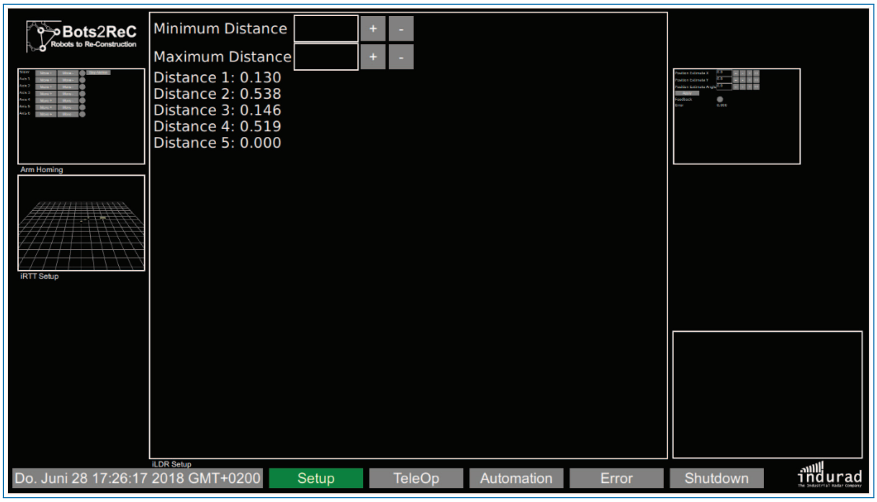


Figure 3.131. 1D radar setup screen.

It is behind the grinding disc. The antenna surfaces have later a distance of 5 to 10cm to the wall.

3.1.51.3 Setup screen and raw distance visualization

The software so far does not allow the configuration of the radars. The next step will allow to set the measurement rate and to define the number of strongest peaks that shall be passed to the robot control software. Also an offset correction will be implemented. A first screen on the iOAU that will be extended has been realized.

3.1.52 Outlook and Future Work to be Carried Out

First samples of the sensors have been developed. Version 1 was not functional, Version 2 is functional but needs optimization. Version 3 is by now available but has not been evaluated yet. Still the PLL loop filter as part of the high frequency generation path must be carefully analyzed and revised. All other hardware related issues are already adapted and corrected, including power management functionality that shall reduce the average power consumption to about 1,3 W. Peak power stays at about 2,5 W.

The interface to the Intel NUC computer has been partly implemented. The radar data stream is transferred. Configuration register are to be added and the motion data stream must be transferred as well. Extended features will allow a detailed setup and monitoring functions, e.g., like temperature and antenna pollution.

The accuracy has been checked in a first trial, the results are used to optimize the firmware that will operate coherent. In addition, mechanical adaptions have been made. This must be now verified with the hardware samples of version 3.

The arm movements must be performed in a direction that allows using the iLDR distance measurements in an optimal way. For example, symmetric situations are problematic, when the grinding direction is in parallel to two sensors next to each other. Then, two sensors are in front of the disc and two are at the rear. The first two sensors are measuring the distance to the surface before grinding, while the two rear sensors are measuring the distance to the processed surface. In this case it cannot be distinguished whether the surface is grinded to a certain depth or the alignment of the disc is wrong. Numerous variations of this example and further more a thinkable and will be evaluated during the ongoing development of the process control to allow a stable grinding process.

3.1.53 Summary and Conclusion

The hardware development for the main system, the 1D radar, are concluded in a preliminary version and will be improved and updated in a second revision, implementing several optimizations. The integration to the software and control is ongoing and continues together with the process development. The same is true for the second system, a force feedback sensor that is functional and integrated but currently not in place. It will be taken into service together with the implementation of an advanced control on the prototype and central process control system.

The third system to monitor the grinding result with cameras is technically available. However, the real camera usage and mount places must be analyzed after the first grinding experiences on the full operational process.

3.1.54 Further System Components

Deliverable Di3.3

Central aspiration and energy supply and safety architecture available

Authors: F. Becchi

3.1.55 Deliverable in the Context of the Work Program

Scope of this internal deliverable is to present proposed implementation of dust aspiration, system energy management and operational test safety. These central systems are used to supply the operational robotic unit during the tests performed and allow a safe testing environment. For the first V1 prototype, the systems are not necessarily designed according to final specifications. Emphasis here is on enabling the prototype rather than testing close to product solutions.

3.1.56 Central Aspiration

The mobile platform is integrated with a local dust aspirator device. This choice was preferred to a centralized aspiration unit to avoid reeled hose connection between the moving robot and the central unit.

After some preliminary discussions, the management of the connecting hoses was discarded not to increase too much the moving robot navigation constraints. In consideration also of a minimal aspiration pipe section of 40 mm the space occupation of a hose pipe reel would have a too strong impact on the overall moving platform dimensions and could not be integrated within the size restrictions. Fist tests will need to show the feasibility of the aspiration as an integrated device, which is now limited in filtering and storage capacity.

For this reason, an asbestos dust aspirator was customized and integrated directly in the platform.

A Pullman Ermator S13 was selected as commercial available starting unit for the following reasons:

- Dust aspiration capability is correctly dimensioned for the tool used in the robot;
- The device is already specific for asbestos dust management;
- The overall dimensions of the aspirator are compatible with the space availability of the platform.

Figure 3.132. Standard asbestos dust extractor and integrated view on the platform.

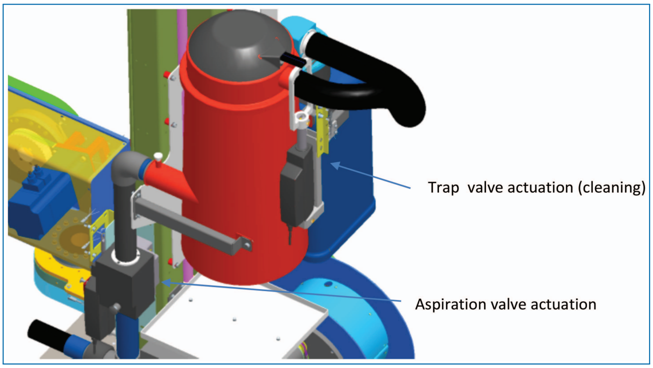


Figure 3.133. Filter cleaning automation.

The aspirator layout was optimized for the platform integration removing the supporting frame with wheels and repositioning the filter unit with respect to the motor unit.

A more in deep device customization was then request to implement the filter cleaning procedure:

In the standard usage the filter cleaning is performed replacing the aspiration pipe with a cap and actuating the cleaning trap valve several times manually.

This same sequence was implemented adding an electrical actuated valve on the aspiration port and adding an electrical actuator to move the cleaning trap valve.

A further system improvement that should be considered for prototype 2 is the automation of dust bag replacement (TBD).

In the reference system configuration the bag is held on the lower section of the filter box with a belt that is manually fastened on the upper bag section. A reliable automated bag replacement could be considered in the final implementation of the

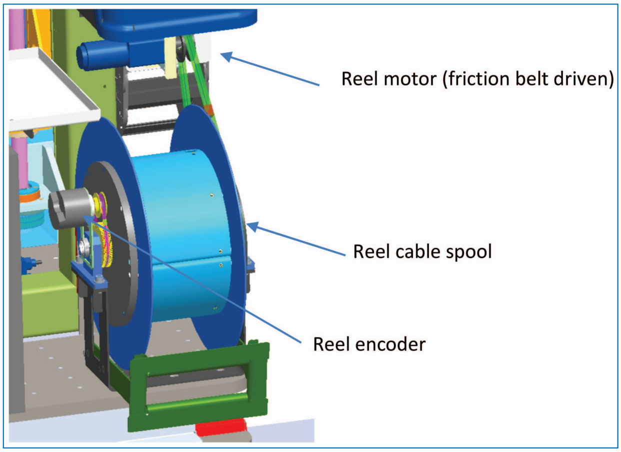


Figure 3.134. Cable reel.

system to allow the robot to change with no external help (cost vs convenience of this feature still to be assessed).

As visible in the above picture the integration of the actuated valve on the aspiration line was also used to reorient the suction pipe to better follow the robot arm in its displacement (on the other side of the platform a dedicate cable chain is used to connect arm actuators with motor driver located on the platform frame).

3.1.57 Energy Supply

The robotic platform is connected to site 230 VAC power lines with a 15 m cable rated for 5 KVA .

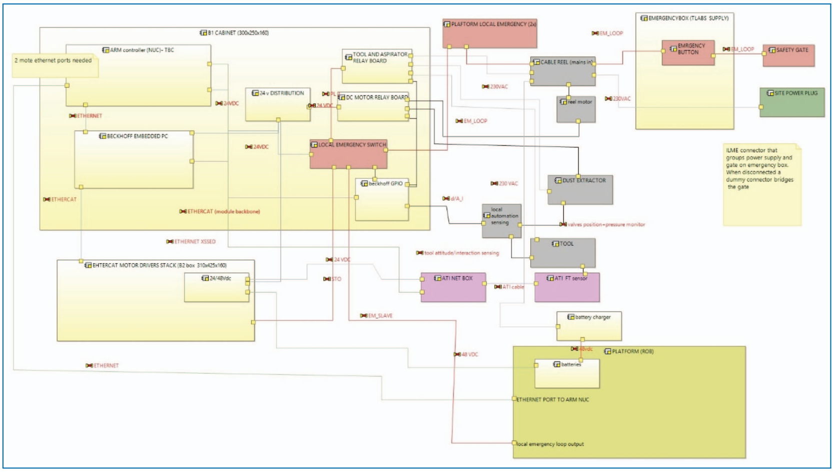


Figure 3.135. System physical block diagram.

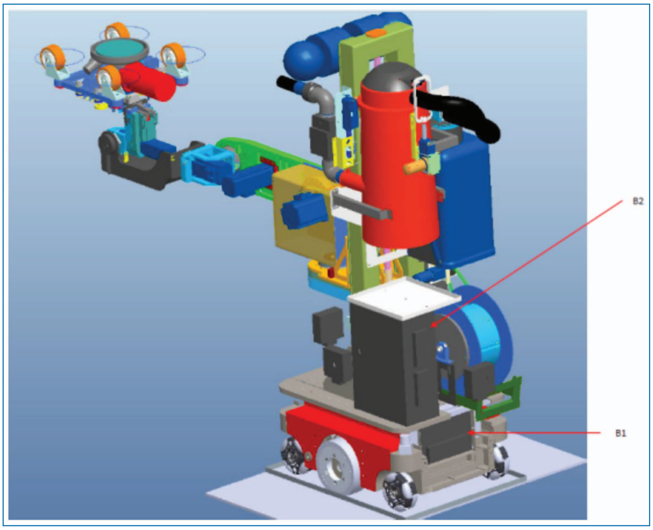


Figure 3.136. B1 and B2 localization in platform integration.

The power supply cable is winded on a custom made cable reel and connected to the platform main power line (on the same power cable some lines are dedicated to system safety management as below discussed).

The cable reel is actuated with a 24VDC motor integrated with a planetary gearhead connected to the cable reel with a friction belt transmission set so to allow cable release in case of overload. The cable reel is also provided with a multi-turn encoder used to measure the estimated amount of cable on the reel.

As shown in the system physical block diagram below reported the 230 VAC line is connected to the platform battery charger and to the asbestos removal tool and dust extractor.

The arm motor drivers board, supplied ad 48VDC, are then directly connected to the main platform battery used as accumulator so to assures when needed high peak power to arm motors. A 48VDC/24VDC converter is used to provide the service power to arm control units (including beckhoff embedded PC and arm NUC) and to drive the on/off electric actuators used for dust extractor cleaning and cable reel actuation.

In terms of electrical integration of the power system management of the platform the main system distribution box in integrated in an IP65 cabinet above identified as “B1” located inside the platform.

48V bus from batteries is connected directly inside the motor driver cabinet “B2” where also the DC/DC converter is integrated.

3.1.58 Safety Architecture

As visible in the physical block diagram an HW safety control loop in integrated in the platform B1 cabinet.

The main unit of the safety control loop is a redundant HW emergency switch that is connected to a redundant chain of emergencies.

The main emergency loop is linked via the tether cable to a main emergency switch that must be located out of the robot operation field. Physical fences provided with safety switch will be connected to the same safety loop through a junction box inside the main switch box (see following operational layout for reference).

To activate the robot platform, in case of need, for site to site transportation, a dummy emergency loop must be connected at the end of the robot tether. For this specific non operational case two emergency buttons positioned at the sides of the main robot structure ensure an acceptable level of user safety. The safety loop disengages the following devices:

- Robot arm actuation (via STO-safe torque off HW control embedded in the arm motor divers);
- Tool and dust extractor 230VAC power supply (via contactor controlled by the safety switch output);
- Platform translation motor (via two paired switch N.O. connected to platform wheels motor control board).

3.1.59 Outlook and Future Work to be Carried Out

The implementation of the works is in the final phase, all systems will be implemented for the V1 prototype. The safety architecture is however going to be finalized on the testing site after all initial robustness test after integration.

3.1.60 Summary and Conclusion

The central systems were implemented as planned, only the aspiration system was decentralized for design reasons and the efficiency of this solution is to be evaluated in the testing phase. In particular the aspiration and storage capacity / run time during operation will give valuable input to the next design phase for V2. The behavior and control of the cable reel will lead to first findings about the feasibility of this approach.

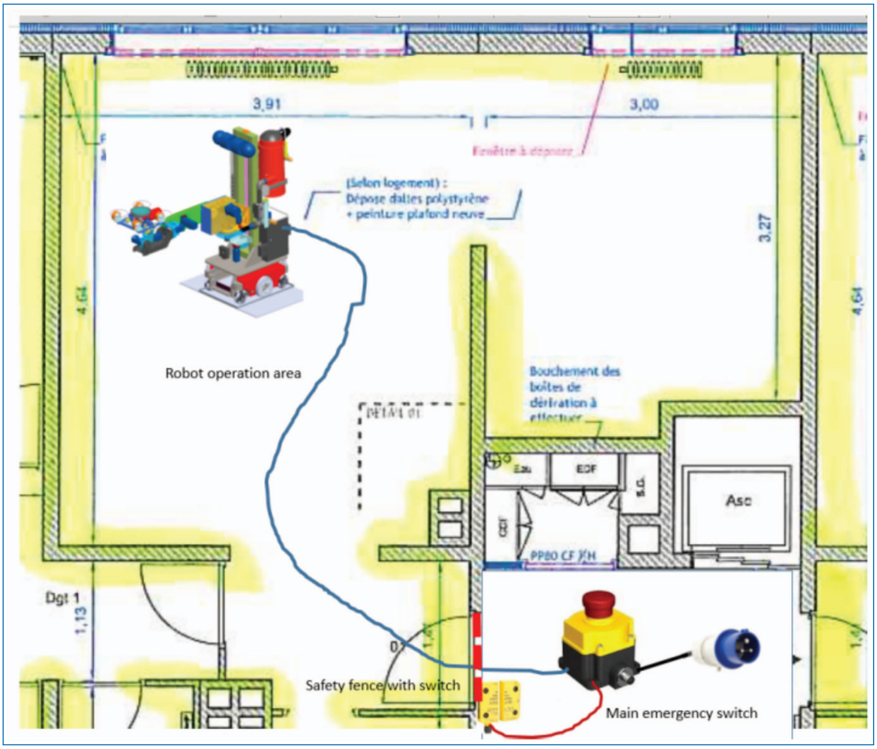


Figure 3.137. Robot operational field integration.

3.1.61 The Entire Systems

Deliverable 3.1
Robotic system V1, ready for the use in the test rehabilitation site

Authors: Daniel Martin (EUT), Ramón Carrasco(EUT), Oriol Orra(EUT)

3.1.62 Deliverable in the Context of the Work Program

The present deliverable report presents one main result of the first period of the project, where a first version (V1) of the Robotic Unit for asbestos removal has been developed. This phase ends with the integration of the different subsystems, designed and developed by the different partners involved in Bots2Rec project. In this document, a main overview of the Robotic Unit V1 is reported, which is a "demonstrator deliverable" as a result of the previous mentioned tasks.

3.1.63 Methods and Work Carried Out

The main components of the Robotic Unit V1 system have been shipped to the system integrators (Eurecat) facilities together with the system documentation (electrical and mechanical diagrams) and set up guidelines. Once the whole set of components has been received, Eurecat, supported by the different partners involved, has proceeded with the full integration, assembly and first test of the Robotic Unit V1. One example of this cooperation between partners on the integration has been a one week workshop where technicians and developers from all of the consortium partners attended for a detailed exchange on all technical levels.

3.1.64 Robotic System V1, Ready for the Use in the Test Rehabilitation Site

In this section the presentation of the Robotic Unit V1 prototype is made, describing the demonstrator deliverable stated in the project plan. This prototype is the result of the integration work and assembly of the different components that have been developed in this first period of the project.

The main components integrated on this first Bots2Rec project prototype are listed below, and shown in Figure 3Figure 3:

- Mobile Platform V1, described in D4.1
- Robotic Arm V1, described in D5.1
- Central Systems and auxiliary devices (aspiration, safety elements, cable reel, …)
- A preliminary working version of the Sensor System for Environmental Perception, to be delivered on 01.08.2017 as Deliverable D4.2

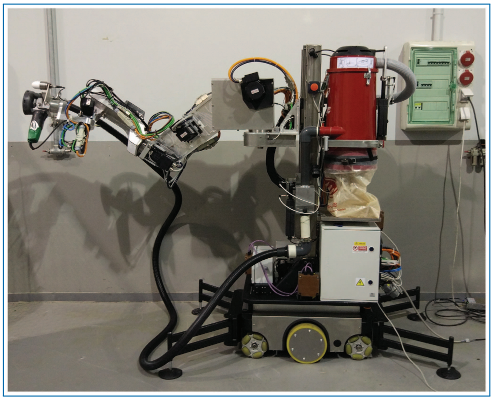


Figure 3.138. General Picture of the Robotic Unit V1.

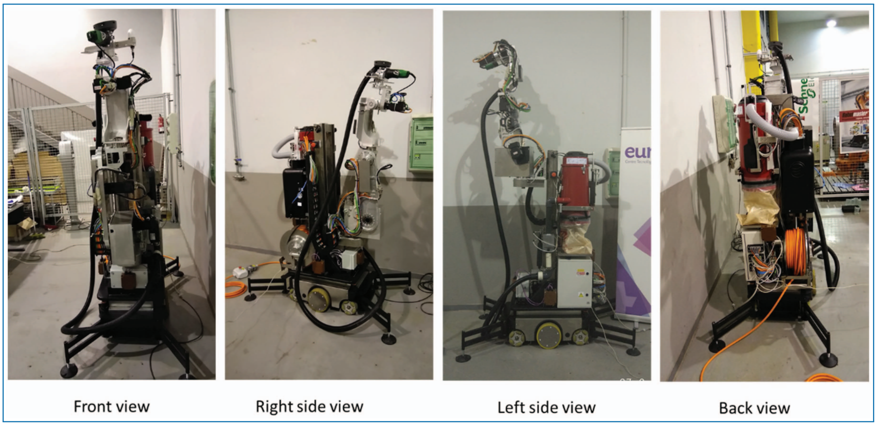


Figure 3.139. Different views of the Robotic Unit V1.

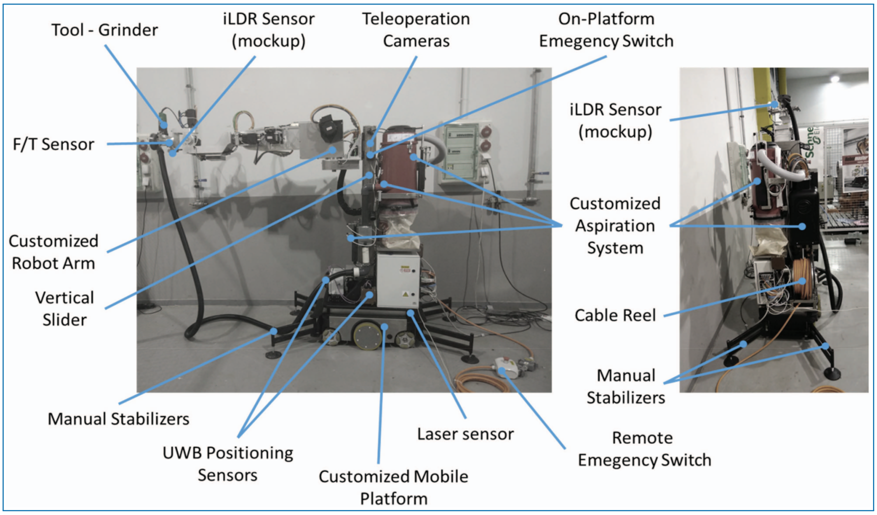


Figure 3.140. Robotic Unit V1 main subsystems.

- A mockup version of the Sensor System for Local Process Monitoring, to be delivered in 01.06.2018 as Deliverable D5.3
- A preliminary working version of the User Interface for Teleoperation, delivered as Deliverable D6.1 together with this Deliverable on 28.02.2017

3.1.64.1 System Assembly

The assembly of all of the components described in the previous section has been performed and all the mechanical and electrical interfaces have been implemented as defined during the design phase of the prototype.

3.1.64.2 Main Functionalities Tests

After the assembly of the main components, the next step has been to test the robotic system performing different motion tests while checking the system stability during these tests. In the following figures some of the performed motion tests are shown. Figure 6 shows the robot reaching its higher position, with the vertical linear axis on its upper limit and the arm completely extended in vertical position.

The most critical position regarding stability is shown in Figure 3.144. It corresponds to the arm completely extended to the front with the upper position of the vertical linear axis.

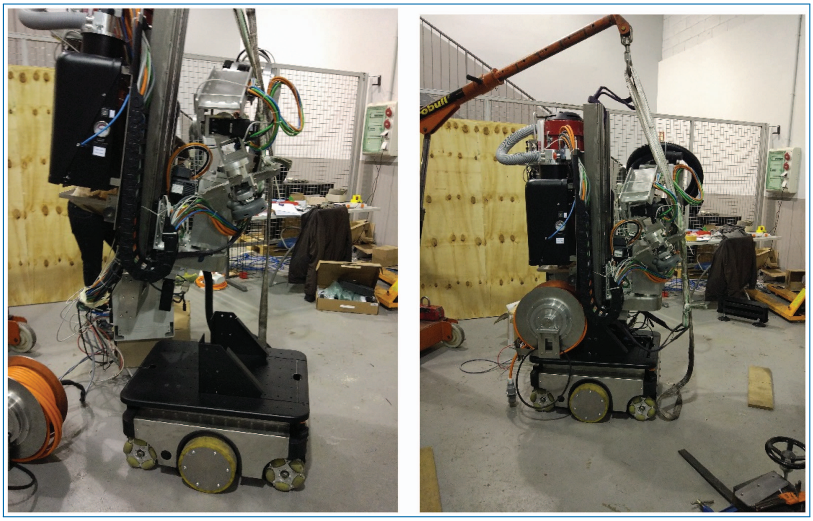


Figure 3.141. Mechanical assembly process of the Robotic Unit V1.

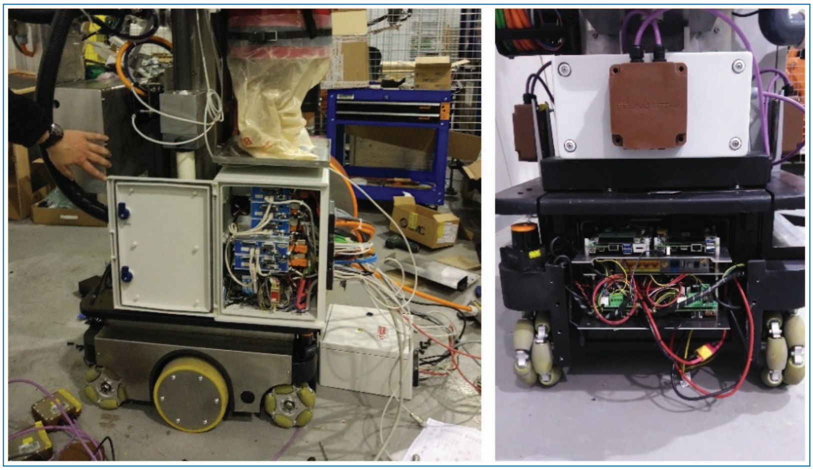


Figure 3.142. Prototype during electrical assembly process.

Figure 3.143. Robot positioned in the top of the vertical linear axis with the arm completely extended to the top.

Figure 3.144. Robot positioned in the top of the vertical linear axis with the arm completely extended to the front.

Figure 3.145 shows the system reaching the floor, ready to perform grinding operations on ground surfaces.

Finally, Figure 3.146 shows the system operator interface for teleoperation in its current working status.

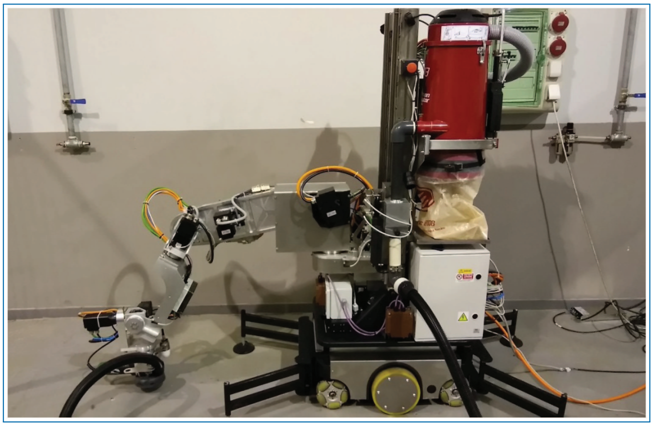


Figure 3.145. System reaching the floor.

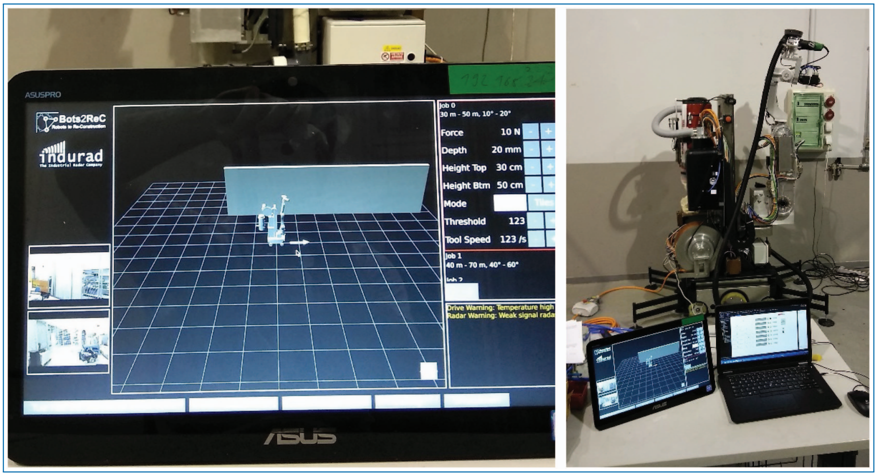


Figure 3.146. Robot Unit V1 operated by the preliminary user interface for teleoperation.

3.1.64.3 Interfaces test

At the time of writing the present deliverable report, a set of intensive tests for checking the proper operation of main control and software interfaces is in process. These tests are going to be performed in the system integrator facilities together with the first operation trials. This is in order to ensure that the major issues that could arise for the robot operation are detected and fixed before shipping the robot to the rehabilitation site, where fewer resources are available. We expect to finish the testing of these interfaces within the next month after the submission of this report.

3.1.65 Outlook and Future Work to be Carried Out

As shown in this report, the Robotic Unit V1 has been successfully integrated and its main functionalities are working. The mechanical and electrical assembly of the different subsystems has been done and tested. Nonetheless, more intensive validation tests (especially of control and software interfaces) need to be performed within the following weeks after this report. With this we can ensure a reliable function and operation of the system in different operational conditions.

As mentioned before, the next step once the prototype is ready, will be to perform the first set of operational test in system integrator facilities in order to detect any important issue in an early phase before shipping the prototype to the rehabilitation site, where fewer resources are available.

3.1.66 Summary and Conclusion

It can be concluded that the Robotic Unit V1 prototype is ready to be used in the rehabilitation side as planned. However, more intensive testing is recommended to be done before the shipment of the prototype, as well as performing a first set of operational tests in the system integrator facilities. This will ensure the systems reliability and avoid further problems on the rehabilitation site.

3.2 Second Robotic Prototype (V2)

3.2.1 Robotic Arm

Deliverable 3.3
Robotic system V2, ready for the use in the test rehabilitation site

Authors: Daniel Martin (EUT), Néstor García (EUT)

3.2.2 Deliverable in the Context of the Work Program

The present deliverable report presents one main result of the second period of the project, where the obtained feedback from the first prototype (V1) of the Robotic Unit for asbestos removal has been applied to an improved second version (V2) of the Robotic Unit. This phase ends with the integration and the complete validation of the different subsystems, designed and developed by the different partners involved in the Bots2Rec project. In this document, a main overview of the Robotic Unit V2 is reported, which is a “demonstrator deliverable” as a result of the previous mentioned tasks.

3.2.3 Methods and Work Carried Out

The main components of the Robotic Unit V2 system have been shipped to the system integrator (Eurecat) facilities together with the system documentation (electrical and mechanical diagrams) and set up guidelines. Once the whole set of components was received, Eurecat, supported by the different partners involved, proceeded with the full integration and assembly of the Robotic Unit V2. Learning from the past experiences and as an attempt to avoid the incurred delays and found problems with the Robot Unit V1, an extremely intense test is conducted at the system integrators facilities to validate the continuous operation of the integrated Robot Unit V2. This validation campaign prior to taking the robot to the testing site is very important to avoid future "debugging actions" that are very difficult and expensive to perform at the testing site (Valence).

3.2.4 Robotic System V2, Ready for the Use in the Test Rehabilitation Site

In this section the presentation of the Robotic Unit V2 prototype is made, describing the demonstrator deliverable stated in the project plan. The described prototype is the result of the integration work and assembly of the different components that have been developed in this second period of the project.

As described in the 2nd periodic report and indicated at the review meeting, the project is experiencing some delay which have affected this deliverable. The main reason that led to this delay have been:

- V1 prototype debugging required an extra effort due to unexpected failures.
- Implementation of prototype V1 not planned upgrades and the need for extra robot maintenance actuations including additional transport to integrator facilities and then back to the testing site.
- Delivery time of critical components (Harmonic Drives, …)

Nevertheless, the integrated robot is available by M40, May 2018. The final version of this deliverable has been prepared after the system integration. It contains all the description of the V2 prototype fully integrated.

The robot (shown in Figures 3.147 and 3.148) is at integrator facilities (Eurecat). The main components integrated on second Bots2Rec project prototype are listed below, and shown in Figure 3.149:

- Two Mobile Platforms V2, described in Deliverable D4.3
- Robotic Arm V2, described in Deliverable D5.2
- Central Systems and auxiliary devices (cable reel, pipe reel …)

Figure 3.147. General Picture of the Robotic Unit V2.

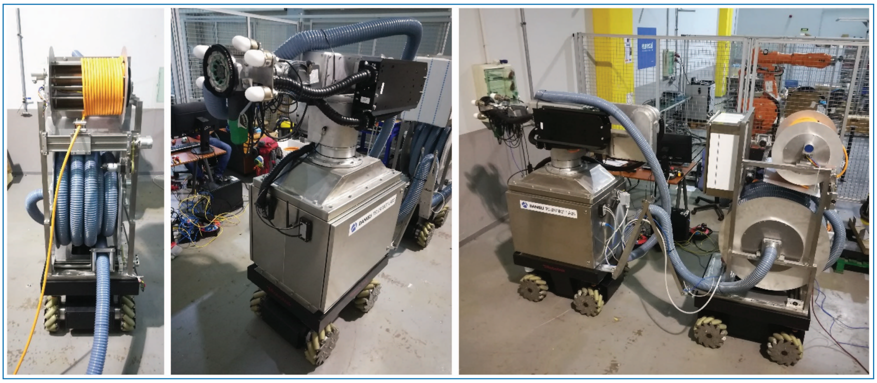


Figure 3.148. Other different views of the Robotic Unit V2.

- External aspiration system
- A working version of the Sensor System for Environmental Perception, described in Deliverable D4.2
- A functional version of the Sensor System for Local Process Monitoring, described in Deliverable D5.3
- A working version of the User Interface for Teleoperation, described in Deliverable D6.1
- A set of tools (see Figure 3):
  - Passive compliance grinding tool
  - F/T sensorized grinding tool
  - Scarifying tool

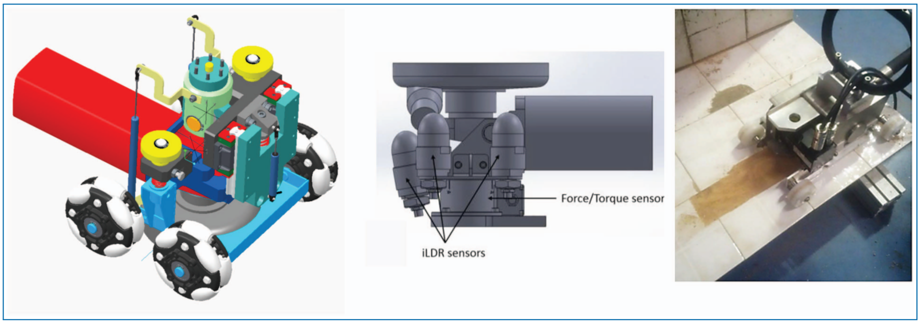


Figure 3.149. Tools of the Robotic Unit V2: Passive compliance grinder (left), F/T sensor grinder (middle), and Scarifier (right).

3.2.4.1 System Assembly

The V2 system assembly has been mostly conducted at the arm manufacturer site (TLABS) unlike the V1 prototype that was mainly assembled (arm to mobile platform) at the integrator facilities (EUT). This fact occurs due to the high level of integration of the arm and its cabinet, which acts as a structural element and need to be assembled directly to the mobile platform. Therefore, arm-to-platform assembly as well as main drive components of the arm have been assembled there.

3.2.4.2 Main Functionalities Tests

After the main assembly, the rest of elements as well as software and communications have been checked and validated at the integrator facilities. The main steps of the prepared validation plan are:

- 1.1 Mechanical integration
  - 1.1.1 All components are correctly assembled
  - 1.1.2 Mechanical interfaces between elements are correctly assembled
- 1.2 Energy Supply
  - 1.2.1 Cabling is correctly disposed and assembled
  - 1.2.2 Connectors and plugs are correctly assembled and connected
  - 1.2.3 Check voltage and correct supply of every component
  - 1.2.4 Measure
- 1.3 Safety elements
  - 1.3.1 Check emergency switch operation
  - 1.3.2 Check other emergency chain elements
- 1.4 Communications

- 1.4.1 Check communication cabling
- 1.4.2 Check configuration of communication elements (router, units IP, comm. speed, etc.)

1.5 Software
1.6 Check sensor data
1.7 Check software command of MP
1.8 Check software command of arm
1.9 Check software command of Aspiration
1.10 Check software of Cable/Pie reels
1.11 Integrated operation

- 1.11.1 Conduct continuous operation test (similar to DiT2.4)
- 1.11.2 Conduct continuous operation test6 (with load)
- 1.11.3 Check of control loops

An intensive effort on the test of the integrated unit has been planned in order to ensure that the major issues that could arise for the robot operation are detected and fixed before shipping the robot to the rehabilitation site, where fewer resources are available.

The motions of the mobile bases have been tested (moving synchronously and independently). Besides, different arm motions have been tested while checking the system stability during these tests. In the following figures some of the performed motion tests are shown. Figure 3.150 shows the robot reaching its higher position and Figure 3.151 shows the robot reaching the lower part of the wall.

The most critical position regarding stability is shown in Figure 3.152. It corresponds to the arm completely extended to the front.

Figure 3.153 shows the system reaching the floor, ready to perform grinding operations on ground surfaces.

3.2.4.3 Interfaces Test

At the time of writing the present deliverable report, a set of intensive tests for checking the proper operation of main control and software interfaces is in process. These tests are going to be performed in the system integrator facilities together with the first operation trials. This is in order to ensure that the major issues that could arise for the robot operation are detected and fixed before shipping the robot to the rehabilitation site, where fewer resources are available. We expect to finish the testing of these interfaces within the next month after the submission of this report.

Figure 3.150. Robot with the arm completely extended to the top.

Figure 3.151. Robot reaching the lower part of the wall.

3.2.5 Outlook and Future Work to be Carried Out

As shown in this report, the Robotic Unit V2 has been successfully integrated and its main functionalities are working. The mechanical and electrical assembly of the different subsystems has been done and tested. Nonetheless, more intensive validation tests (especially of control and software interfaces) need to be performed within the following weeks after this report. With this we can ensure a reliable function and operation of the system in different operational conditions.

Figure 3.152. Robot positioned in the top of the vertical linear axis with the arm completely extended to the front.

Figure 3.153. System reaching the floor.

As mentioned before, the next step once the prototype is ready, will be to perform the first set of operational test in system integrator facilities in order to detect any important issue in an early phase before shipping the prototype to the rehabilitation site, where fewer resources are available.

3.2.6 Summary and Conclusion

It can be concluded that the Robotic Unit V2 prototype is fully integrated and working. However, more intensive testing is recommended to be done before the shipment of the prototype, as well as performing a first set of operational tests in the system integrator facilities. This will ensure the systems reliability and avoid further problems on the rehabilitation site.

Deliverable 5.2
D5.2 Robot Arm V2 tested and ready for integration to the robotic system

Authors: F. Becchi

3.2.7 Deliverable in the Context of the Work Program

This deliverable is an output from WP 5: Customization of the robotic arm: Design, control and implementation and in particular from Task 5.5 Testing of the sub system.

The deliverable resumes the outcomes of the test procedure implemented on the V2 robotic arm before its shipment to the integration site.

3.2.8 Methods and Work Carried Out

With reference to the Robotic System V2 architecture, this report focus to the set of subsystem integrated with the robotic arm.

More specifically the modules that will be covered in this test report are

- Robotic Arm

In line with TLABS QC system FAT (final acceptance test) is managed through a test procedure aimed at the incremental verification and validation of all relevant subsystems.

The main structure of the test sequence covers the different topics resumed in the list below reported:

1.0 arm integration

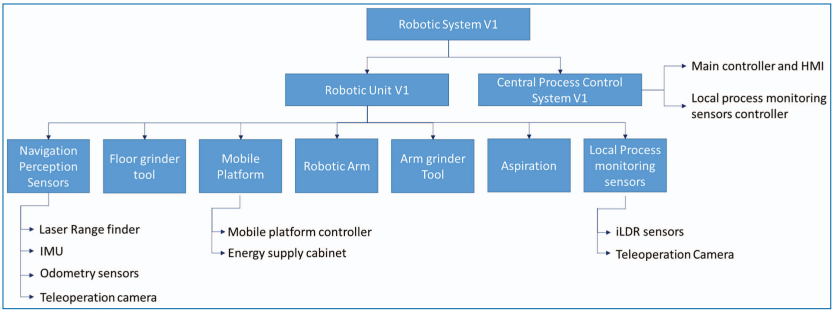


Figure 3.154. General system architecture.

Figure 3.155. Arm assembly.

1.1 robot arm power supply
1.2 robot arm electrical interfaces
1.3 emergency loop ok
1.4 motor calibration
1.5 ethercat network configuration ok- motors
1.6 ethercat network configuration ok- IOS
1.7 tool
1.8 arm calibration check
1.9 arm test sequence

The following section will details the results of the test performed.

3.2.9 Robot Arm Test Report

3.2.9.1 Arm Integration

Scope of this first test is to check that robot arm and main subsystems are correctly integrated according to the reference CAD model.

The reference CAD model considered for this purpose is the T000120A100.asm shown below for reference. The following table summarizes tests done and results achieved.

As visible in the above table all robot arm subsystems are correctly installed. Tool is currently not included in the integration. A review on the "reference" tool was performed and a new tool is currently in construction.

The following pictures show some views of the system being integrated.

Table 3.3. Tests and results.

§	Short	Description	ok	nok	NA	Ref.	Remarks
1.0	arm integration	robot arm and main subsystems are correctly integrated according to reference CAD model	x				
1.0.1	robot arm is correctly assembled		x				
1.0.2	robot arm is integrated on robot cabinet		x				
1.0.3	tool is integrated on the robot			x			tool integration is postponed with respect to arm integration
1.0.4	cabinet is integrated with the motor drivers, Beckhoff CPU and other auxiliary components		x				
1.0.5	robot arm is electrically connected to robot cabinet		x				

3.2.10 Outlook and Future Work to be Carried Out

Within the next weeks, the following test will be performed in order to ensure, that the robotic arm is ready for the final integration at Eurecat facilities.

Figure 3.156. Arm assembly.

Figure 3.157. Arm integration.

Test schedule:

1. Robot arm power supply
2. Robot arm power electrical interfaces
3. Emergency loop ok
4. Motor calibration
5. Ethercat network configuration ok- motors network
6. Ethercat network configuration ok- I/O network
7. Beckhoff arm calibration test
8. Tool
9. Arm test sequence

This deliverable will be updated accordingly as soon as the tests are finalized.

3.2.11 Summary and Conclusion

The robotic arm for the V2 prototype was manufactured and assembled. First tests have been performed with satisfying results. Before the robots will be shipped to the Eurecat facilities for the final integration, further tests will be done according to the above listed schedule. After completion, this deliverable will be updated and finalized.

ANNEX: Full Table To Be Completed

§	Short	Description	ok	nok	NA	Ref.	Remarks
1.0	arm integration	robot arm and main subsystems are correctly integrated according to reference CAD model					
1.0.1	robot arm is correctly assembled		x				
1.0.2	robot arm is integrated on robot cabinet		x				

§	Short	Description	ok	nok	NA	Ref.	Remarks
1.0.3	tool is integrated on the robot		x				tool integration is postponed with respect to arm integration
1.0.4	cabinet is integrated with the motor drivers, bechoff CPU and other auxiliary components						
1.0.5	robot arm is electrically connected to robot cabinet						
1.1	robot arm power supply	the robot arm power supply is correctly managed and is ready for system integration					
1.2	robot arm electrical interfaces	connection btw robot arm and platform are compliant with the defined interface					

§	Short	Description	ok	nok	NA	Ref.	Remarks
1.3	emergency loop ok	the emergency loop is correctly implemented and working					
1.4	motor calibration						
1.5	ethercat network configuration ok- motors	all motors are correctly mapped of the beckhoff PC via ethercat protocol					
1.6	ethercat network configuration ok- IOS	all IOS are correctly mapped of the beckhoff					
1.7	tool	tool can be activated b dedicated beckhoff output signal					
1.8	arm calibration check	beckhoff sw manage robo calibration.					
1.9	arm test sequence	simple test sequence is implemented o beckhoff. Moto are moved on b on and the low level configuration contro stops motion in case of need.					

Deliverable 3.3
Robotic system V2, ready for the use in the test rehabilitation site

Authors: Daniel Martin (EUT), Néstor García (EUT)

3.2.12 Deliverable in the Context of the Work Program

The present deliverable report presents one main result of the second period of the project, where the obtained feedback from the first prototype (V1) of the Robotic Unit for asbestos removal has been applied to an improved second version (V2) of the Robotic Unit. This phase ends with the integration and the complete validation of the different subsystems, designed and developed by the different partners involved in the Bots2Rec project. In this document, a main overview of the Robotic Unit V2 is reported, which is a "demonstrator deliverable" as a result of the previous mentioned tasks.

3.2.13 Methods and Work Carried Out

The main components of the Robotic Unit V2 system are being shipped to the system integrator (Eurecat) facilities together with the system documentation (electrical and mechanical diagrams) and set up guidelines. Once the whole set of components is received, Eurecat, supported by the different partners involved, will proceed with the full integration and assembly of the Robotic Unit V2. Learning from the past experiences and as an attempt to avoid the incurred delays and found problems with the Robot Unit V1, an extremely intense test will be conducted at the system integrators facilities to validate the continuous operation of the integrated Robot Unit V2. This validation campaign prior to taking the robot to the testing site is very important to avoid future "debugging actions" that are very difficult and expensive to perform at the testing site (Valence).

3.2.14 Robotic System V2, Ready for the Use in the Test Rehabilitation Site

In this section the presentation of the Robotic Unit V2 prototype is made, describing the demonstrator deliverable stated in the project plan. The described prototype is the result of the integration work and assembly of the different components that have been developed in this second period of the project.

By the moment of presenting this deliverable, the complete integration of the robotic system V2 still in progress because of different delays. As described in the 2nd periodic report and indicated at the review meeting, the project is experiencing

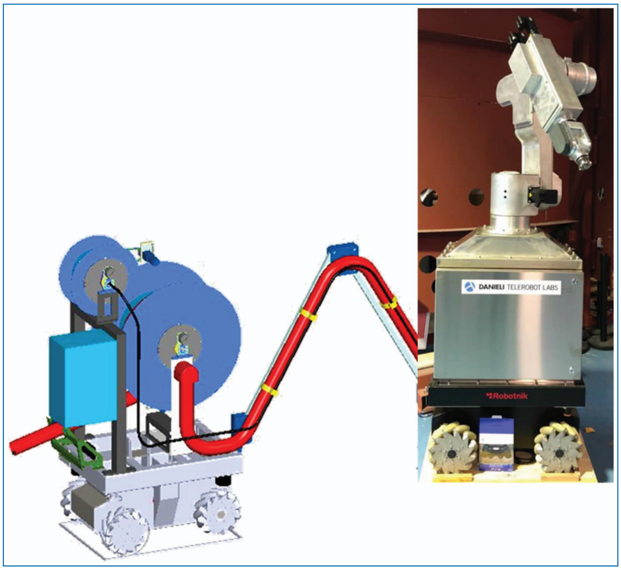


Figure 3.158. General Picture of the Robotic Unit V1.

some delay which affects this deliverable. The main reason that led to this delay have been:

- V1 prototype debugging required an extra effort due to unexpected failures.
- Implementation of prototype V1 not planed upgrades and the need for extra robot maintenance actuations including additional transport to integrator facilities and then back to the testing site.
- Delivery time of critical components (Harmonic Drives, …)

The availability of the integrated robot is expected by M36, January 2018. The final version of this deliverable will be prepared after this system integration. It will contain all the description of the V2 prototype fully integrated, tested and ready to be used at the testing site.

The current status (shown in Figure 3.158) is:

- Mobile Platform of FRONT unit is available and ready for integration and available at arm integrator facilities (TLABS)
- 7 DoF arm is mechanically integrated as well as the electrical cabinets, which act at the same time as structural element of the FRONT unit. It is missing the integration of most of the electrical equipment of the arm. This works are in progress at arm integrator facilities (TLABS)
- Communication elements and sensors will be installed at system integrator facilities (Eurecat)

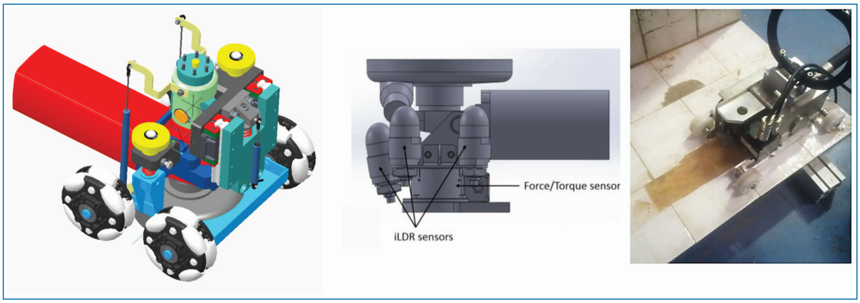


Figure 3.159. Tools of the Robotic Unit V2: Passive compliance grinder (left), F/T sensor grinder (middle), and Scarifier (right).

- Software integration at system integrator facilities (Eurecat)
- Connection between FRONT and REAR unit still in progress.
- New set of Local process monitoring still in progress.
- All components of REAR unit still in progress

The main components integrated on second Bots2Rec project prototype are listed below, and shown in Figure 3:

- Two Mobile Platforms V2, described in Deliverable D4.3
- Robotic Arm V2, to be described in Deliverable D5.2
- Central Systems and auxiliary devices (cable reel, pipe reel …)
- External aspiration system
- A working version of the Sensor System for Environmental Perception, described in Deliverable D4.2
- A functional version of the Sensor System for Local Process Monitoring, described in Deliverable D5.3
- A working version of the User Interface for Teleoperation, described in Deliverable D6.1
- A set of tools (see Figure 3.159):
  - Passive compliance grinding tool
  - F/T sensorized grinding tool
  - Scarifying tool

3.2.14.1 System Assembly

The V2 system assembly will be mostly conducted at the arm manufacturer site (TLABS) unlike the V1 prototype that was mainly assembled (arm to mobile platform) at the integrator facilities (EUT). This fact occurs due to the high level of integration of the arm and its cabinet, which acts as a structural element and need to be assembled directly to the mobile platform. Therefore, arm to platform assembly as well as main drive components of the arm will be assembled there.

3.2.14.2 Main Functionalities Tests

After this initial assembly, the rest of elements as well as software and communications will be assembled, checked and validated at the integrator facilities. A validation plan is being prepared accordingly, which main steps will be:

- 1.1 Mechanical integration
  - 1.1.1 All components are correctly assembled
  - 1.1.2 Mechanical interfaces between elements are correctly assembled
- 1.2 Energy Supply
  - 1.2.1 Cabling is correctly disposed and assembled
  - 1.2.2 Connectors and plugs are correctly assembled and connected
  - 1.2.3 Check voltage and correct supply of every component
  - 1.2.4 Measure
- 1.3 Safety elements
  - 1.3.1 Check emergency switch operation
  - 1.3.2 Check other emergency chain elements
- 1.4 Communications
  - 1.4.1 Check communication cabling
  - 1.4.2 Check configuration of communication elements (router, units IP, comm. speed, etc.)
- 1.5 Software
- 1.6 Check sensor data
- 1.7 Check software command of MP
- 1.8 Check software command of arm
- 1.9 Check software command of Aspiration
- 1.10 Check software command of Cable/Pipe reels
- 1.11 Integrated operation
  - 1.11.1 Conduct Integrated Robot Unit V2 continuous operation test (similar to DiT24 test)
  - 1.11.2 Conduct Integrated Robot Unit V2 continuous operation test (with load)
  - 1.11.3 Check of control loops

An intensive effort on the test of the integrated unit is planned in order to ensure that the major issues that could arise for the robot operation are detected and fixed before shipping the robot to the rehabilitation site, where fewer resources are available.

3.2.15 Outlook and Future Work to be Carried Out

As shown in this report, the integration of the Robotic Unit V2 has been initiated. By the time of writing this report, some tasks regarding the arm assembly and its integration to the mobile platform are in progress at the arm developer facilities.

After that, all the V2 system components will be received at the system integrators facilities in order to finish the integration process, including hardware and software.

Next step will be an intensive validation test campaign at the system integrator facilities will be conducted in order to ensure a reliable function and operation of the system in different operational conditions.

3.2.16 Summary and Conclusion

It can be concluded that the Robotic Unit V2 prototype is delayed and, therefore, not ready yet to be used in the rehabilitation side as planned. Some integration task still in progress and some of them will be initiated within next months.

One of the lessons learned with the previous prototype is the fact that before the Robotic Unit V2 prototype can be considered as ready to be used in the rehabilitation site as planned, extremely intensive tests must to be conducted in the system integrator facilities. This will ensure the systems reliability and avoid further problems on the rehabilitation site and related delays.

3.2.17 Radar Sensors

Task 4.2 Sensor Systems for environmental perception

The autonomous mobile front and rear units use 2D-SLAM (simultaneous localization and mapping) algorithms to navigate inside buildings through rooms and around obstacles. Each unit is equipped with two iSDR-C (indurad Scanning Dynamic Radar – Compact, Figure 3.160) sensors mounted on the front-right and rear-left side of the mobile base of the each unit as depicted in Figure 3.160.

The iSDR-C was still a prototype at the early stages of the project. Its development has been advanced in the last two years, and it reached the point of product maturity. The radar sensor performs a 360° round scan with reliable measurement of distances to any surface capable of reflecting the radiated microwave in a frequency band centred around 77 GHz. The iSDR-C offers an extremely high update rate of up to 1600 measurements per second and an accuracy of down to < 10 mm depending on the measured range and the radar-configuration.

The raw data consisting of sampled received radar waves and the associated angles are sent via Ethernet to an embedded computer (Intel-NUC) for digital signal processing. The results of the processing are arrays of frequency-spectrum power intensities corresponding to the scanning radial line from the sensor. These frequencies correspond to distances from reflecting objects around the sensor. The peaks in the spectrum caused by these targets and the incident angle are converted to cloud-points. These points are sent to the main ROS-computer and used by the 2D-SLAM algorithms developed at IGMR-RWTH. Figure 3.161 through Figure 3.162 show typical iSDR-C radar images and the corresponding ROS cloud-points.

Task 5.2 Sensor system for local process monitoring

The control and placement of the grinding tool by the robot arm requires accurate measurements of the distance between the tool and the wall. The arm of the V2 robot is equipped with five iLDR-C (indurad linear dynamic radar – compact, Figure 3.163) sensors as depicted in Figure 3.164.

iLDR-C V1 sensors were tested on the V1 robot in the early stages of the project. The current iLDR-C sensors mounted on the V2 front unit robot are of the latest version, V4, at this time. None linearity, misplacement of the radar chips and detection of very close objects are critical issues that were faced during workshops with the V1 and V2 robots, which were addressed in deliverable D5.3. Since then a lot of work has been done to resolve these issues and mitigate their impact on

Figure 3.160. iSDR-C mounted on the front unit.

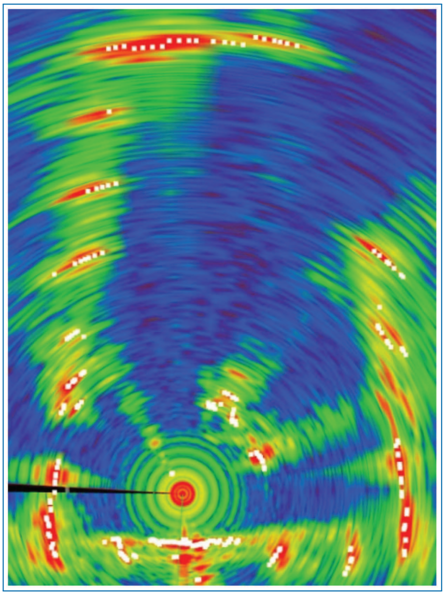


Figure 3.161. Radar image showing cloud-points.

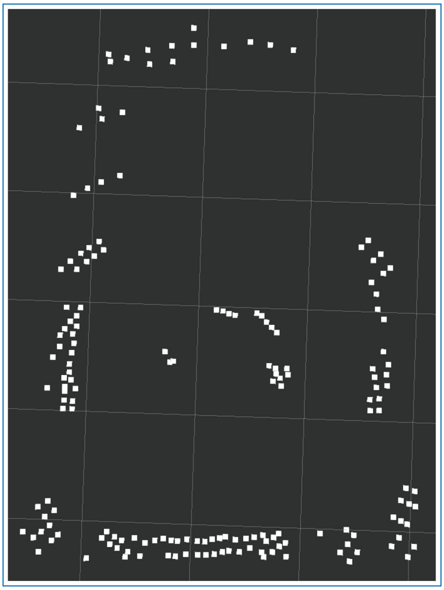


Figure 3.162. Cloud-points in ROS visualization (RViz).

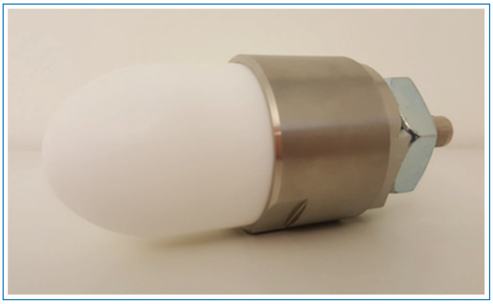


Figure 3.163. iLDR-C front view showing the PTFE lens.

the accuracy of the measurement. The following paragraphs will briefly discuss the work done.

The linearity of the radar measurements was investigated in a series of experiments using a linear axis with a stepping motor. The following diagrams show the relationship between the real distances to a target compared with radar measurement. The plot at the top of Figure 3.165 shows a linear relationship at first glance. Zooming in to region around zero in the third plot of the figure shows a none-linear offset. Figure 3.166 shows the same measurements taken varying speeds (1 mm/s–10 mm/s).

Figure 3.164. Five iLDR-C mounted on the tool.

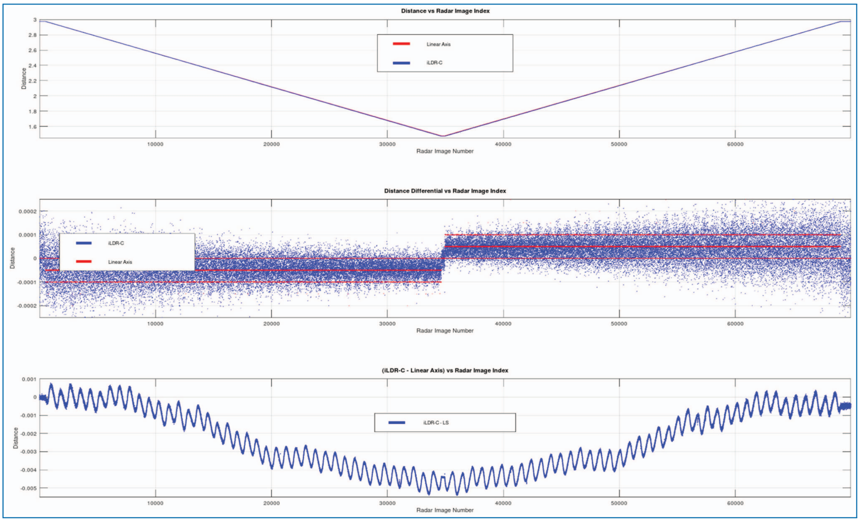


Figure 3.165. Linear axis moving with constant speed of 1 mm/s.

Further investigation of these and several other experiments led to corrections applied to the setup and configuration of the PLL (phased locked loop) and radar parameters (bandwidth, start and end frequencies, etc.).

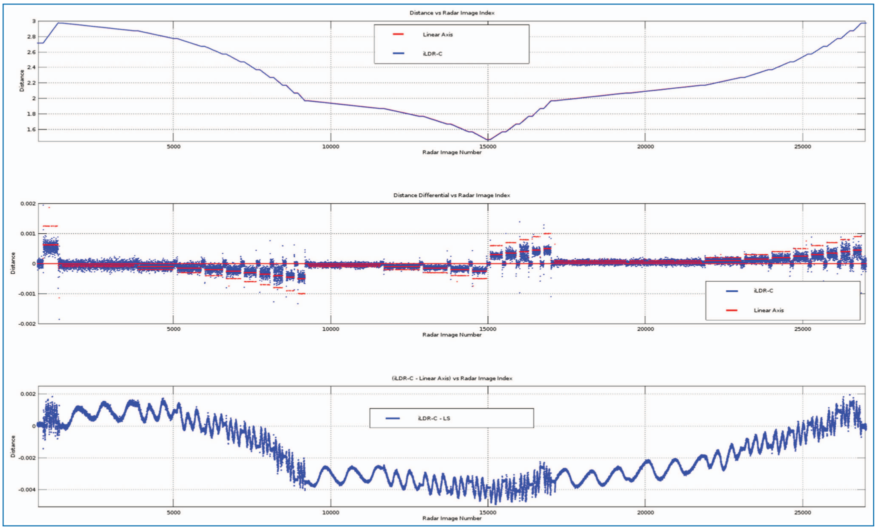


Figure 3.166. Linear axis moving at different speeds (1 mm/s–10 mm/s).

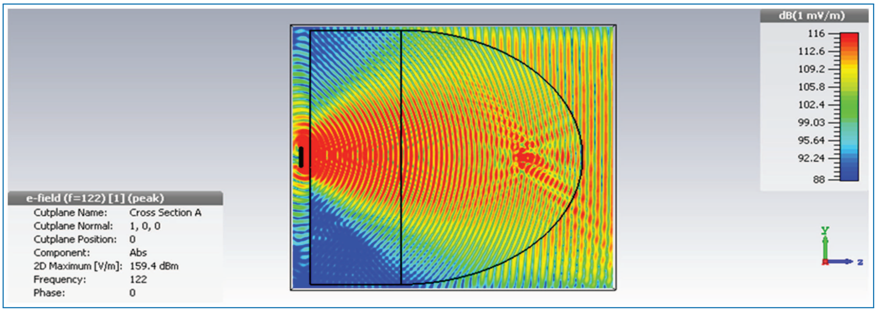


Figure 3.167. Simulating the propagation of the electromagnetic waves thought the lens.

The issue concerning the misplacement of the lens had a bigger impact on the accuracy of the radar measurements. Figure 3.167 shows a simulation of electromagnetic field propagation in a PTFE lens, which converts the spherical field to a plane wave and achieving 32 dB.

In reality though, a bi-static radar, i.e. a radar with separate transmitting and receiving antennas cannot be optimally a placed under a radome. The first iLDR-C versions suffered of this misalignment. The following figures shows simulation results of the placement of the radar chip in iLDR-C V4.

Figures 3.168 and 3.169 show simulation results of the receive and transmitting antennas optimally placed to mitigate the misalignment due to the nature of bi-static radars.

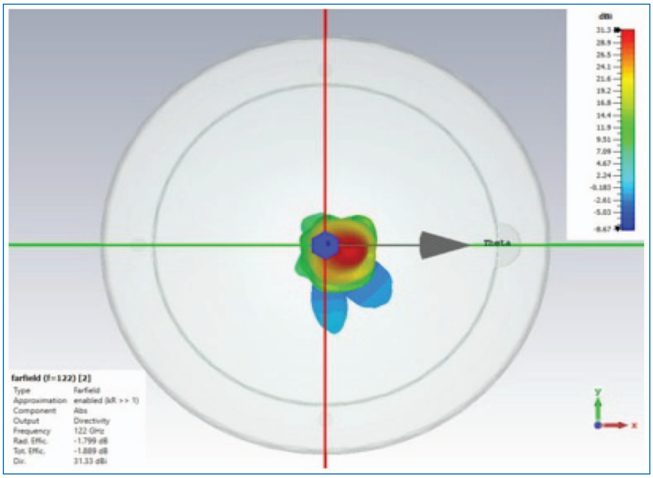


Figure 3.168. Receive antenna.

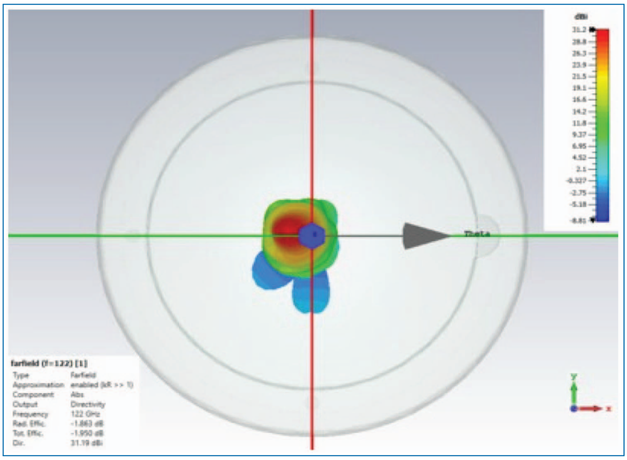


Figure 3.169. Transmitting antenna.

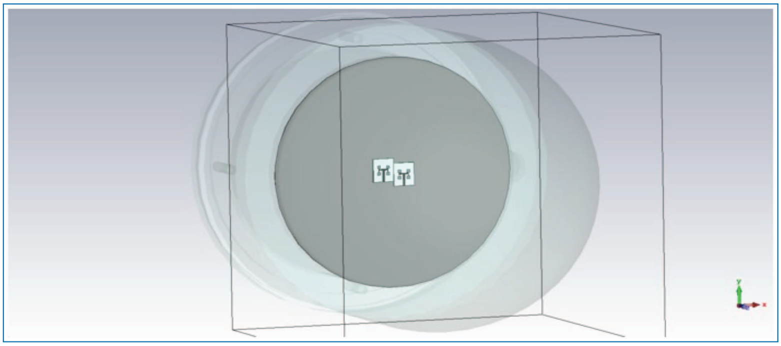


Figure 3.170. Alignment of transmitting and receiving antennas under the lens.

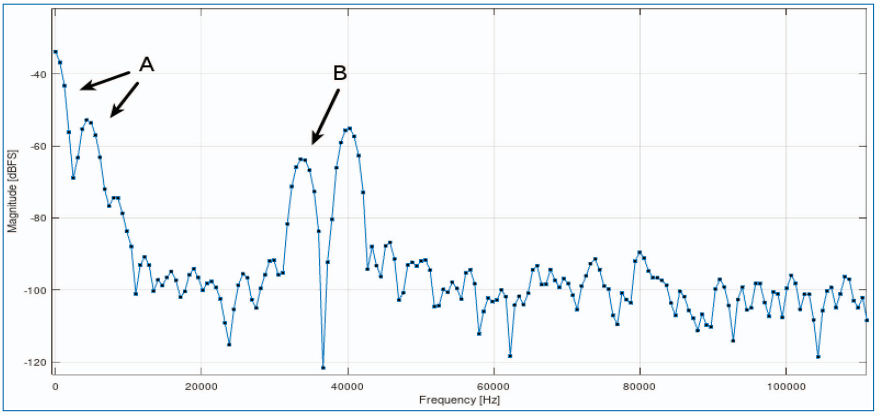


Figure 3.171. Frequency spectrum showing the effect of the lens. A: Static clutter due to the lens. B: Targets 80 cm away from the sensor.

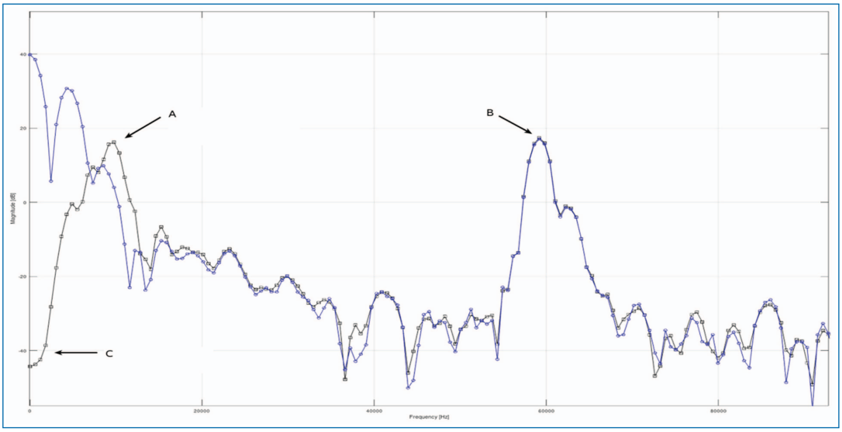


Figure 3.172. Effect of applying a high-pass filter to remove the reflections of the lens. A: Close target. B: Far target. C: DC-leakage and lens attenuated by 80 dB.

The PTFE lens affects the detection of targets close to sensor. Reflections of target in the range of 10 cm in front of the lens are difficult to separate from reflections of the lens. The reflections of the lens are always present and hence are considered static clutter. The following frequency spectrum plot shows the effect of thelens.

Several methods for the mitigation of the impact of the lens on close targets were investigated. The first and simplest method is applying a high-pass filter with a cutoff frequency corresponding to the reflection of the lens. Several filter designs and configurations were tested.

Figure 3.172 shows the effect of a 9th order Chebychev 2 IIR high-pass filter implemented in five second- order sections. This approach was not satisfying

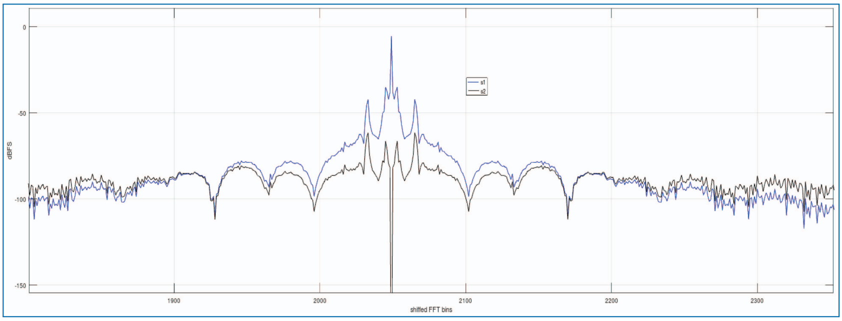


Figure 3.173. SVD method. S1: Original signal showing high peak in the middle of the plot corresponding to static clutter. S2: Result of removing the lens, as it was the strongest signal in the measurement.

enough to be adopted. The high-pass filter damped the signals of the targets as they moved closer to the lens.

The second approach was the method of SVD (singular value decomposition). Using this method, the radar signals could be separated according to the spectral law of linear algebra in several matrices representing signal and noise spaces.

Figure 3.173 shows the effect of applying the SVD method to remove static clutter of the measurement. In this case, the signal of the lens was the strongest. Hence, it corresponded to the largest singular value. Subtracting the matrix of the signal space corresponding to this singular value removed the static clutter of the lens from the total signal.

The SVD method was considered from a theoretical point of view and was further not implemented in the project. The third method investigated was the simplest and most effective one. A pre-recorded signal corresponding to the lens is subtracted from each measurement. This pre-recorded signal was measured with no targets in 20 meters in front of the sensor, leading to the lens being the only or at least the strongest target. This method is currently implemented in the signal processing software of the iLDR-C system on the V2 robot.

Figures 3.174 and 3.175 show screenshots from the signal processing software running on the V2 robot. The effect of subtracting the pre-recorded lens signal is clearly demonstrated.

3.2.18 Further System Components

Task 3.4 Implementation of central systems

In this task the central systems, that are not part of the robotic units or the central process control system were layout, implemented and tested. For the V2 robot the suction system is external to the robot to provide more suction power and to be

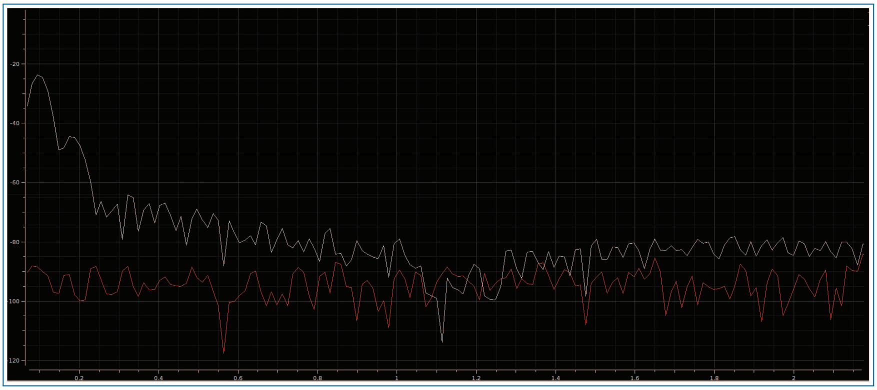


Figure 3.174. White plot shows the original signal. Red plot shows the signal after subtracting the lens siganl.

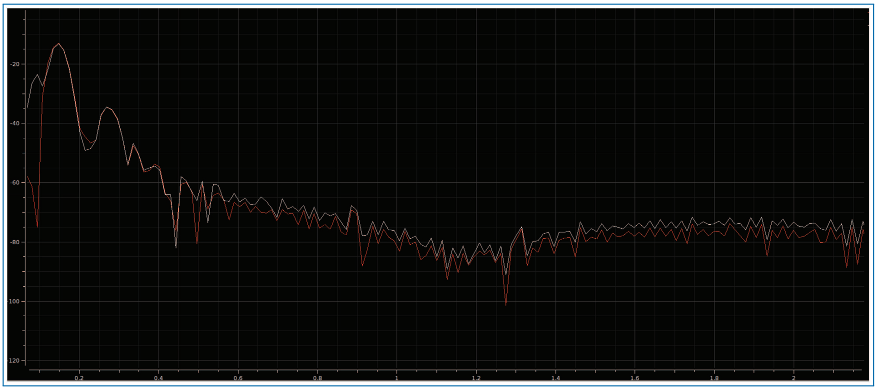


Figure 3.175. The red plot shows a strong peak by a wall 4 cm in front of the sensor. The wall is easily separated from the strongly attenuated lens reflection.

able to centralize the collection of contaminated material from all units in operation. In this way, the robot was provided with an aspiration hose connected to the suction system, which is picked up and released when the robot moves. These pipe-reeling system was designed, implemented and, then, tested in manual and automatic mode. The robot was also provided with two safety switches, one for each mobile platform, so both buttons can safely stop the robot, during the testing and benchmarking phase operation. When pressing the emergency stop, the wheels and joints of the arm are blocked in such a way that they prevent the movement of the robot as well as putting pressure on any object by the effect of gravity, increasing the safety of the system. The emergency stop was tested, with both units working in tandem configuration and working independently (in this case, each button stops the corresponding mobile platform).

A reel unit was integrated on the robot following platform as discussed in the second periodic report. To extend the reach of the robotic system without affecting

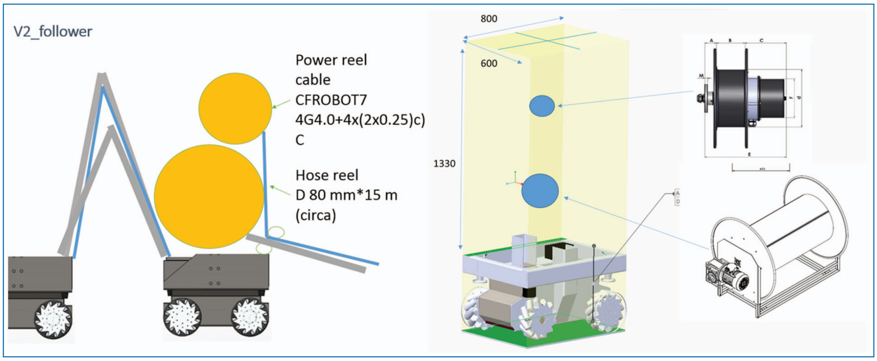


Figure 3.176. Reel unit components.

dust removal performance the original concept of a single fully integrated robot evolved in two paired robotic platform with the flowing one supporting the operation of the main robotic arm with aspiration hose reel and power supply cable reel. The following figure summarizes first approximation detailed requirement for the two reels to be integrated and a rough dimensional reference for the development of the reel units.

As for the first prototype after a first discussion with industrial reels supplier we opted for a fully custom design with the aim of optimizing dimensional integration. As visible in the integration pictures below reported the overall concept of the two reels is based on the same design implemented and tested for the cable reel for the V1 prototype.

As in the first design, a sliding belt transmission is implemented between the reel and the motor where, also in this case, drum position is directly read with an independent belt transmission, read on the Ethercat interface with a dedicated multiturn encoder.

The novel feature introduced in this case is the fully programmable reeling unit on the two reels:

Cable/hose position is guided along the reel thanks to a motor driven guide. Cable/hose position can be as consequence controlled to follow the reel rotation and to guide the correct cable/hose winding. This is useful for cable reel but is of paramount importance for the hose reel where large hose diameter aspiration pipe fills nearly completely the reel (see picture above). The reel unit is completed by a local control cabinet (see picture below) that integrates local Ethercat module, connected to the main controller, and the needed power distribution.

Task 4.3 Control of the mobile platforms

The two reels unit integrated in the auxiliary robot platform are integrated in terms of control in the same Ethercat network of the main robot arm drivers. The local

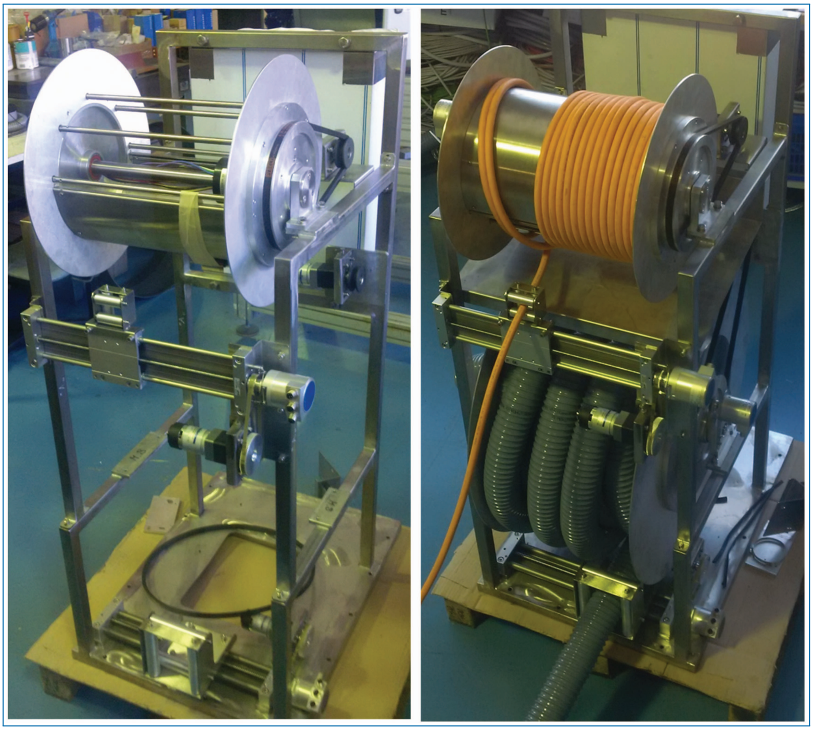


Figure 3.177. Mechanical integration.

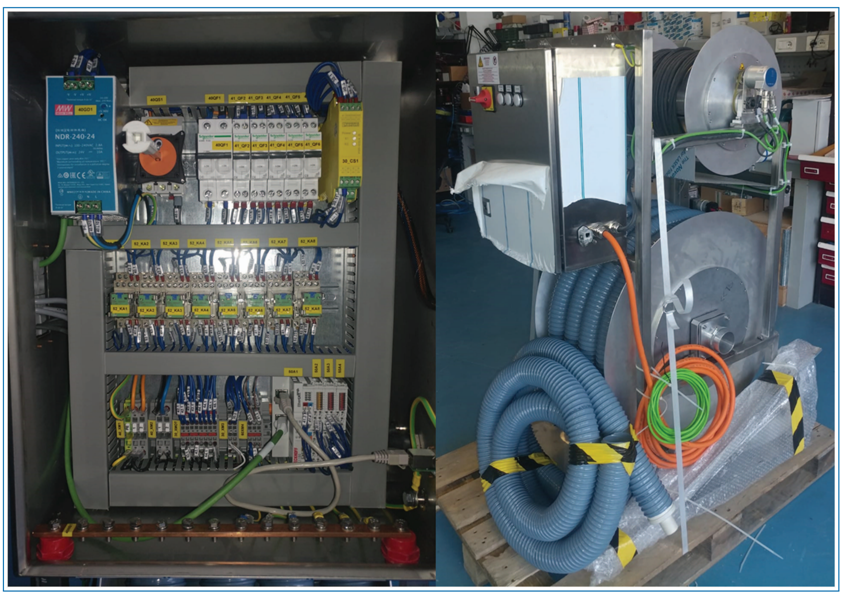


Figure 3.178. Final integration, system ready for shipment.

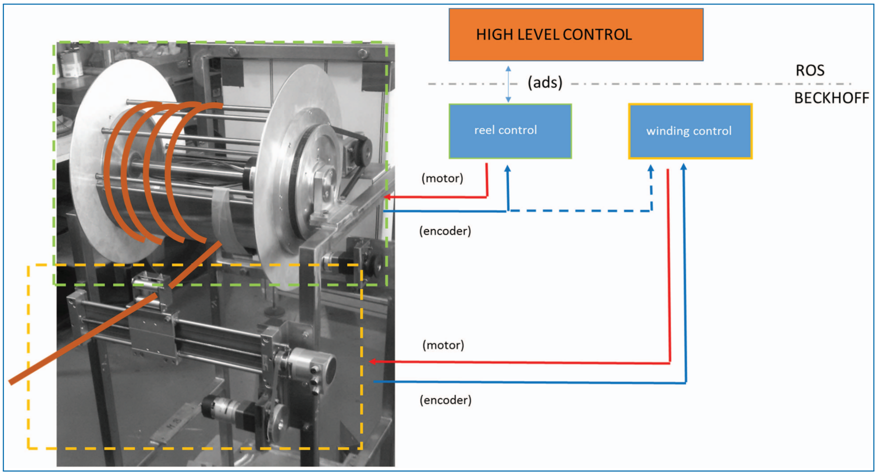


Figure 3.179. Reel control.

network implemented on the reel unit manage four multi-turn absolute encoders and four electric motor.

The processes managing the reels are integrated in the Beckhoff CPU installed in the main robot cabinet as ,at least in the actual implementation, there is no need to use the reel unit decoupled from the robot arm.

The reel/unreel control can be controlled directly from the ADS interface via ROS, to manage cable/hose length together with platform motion control. Alternatively, reels can be left "idle" so that the cable/hose is unreeled passively (reeling is always actuated).

Winding guide control is a parallel low-level process running independently by the reel control: the reel rotation angle is fed to the winding guide control that as consequence adapt cable position so the cable always follow (with actuated or idle motion) the reel.

3.2.19 Entire System

Task 3.5 Assembly and validation tests of the robotic system

Robot arm integration and testing was performed right at the end of the 2nd reporting period, as anticipated in the previous technical report. The full robot arm was integrated and tested in DTLAB facilities in Genova before shipment to integration site. Detailed test report can be found on D5.2.

Some pictures of the robot arm integrated under test extracted from this deliverable are here reported as reference. As visible the main goal of a cleaner integration of robot arm different subsystem can be considered met. The amount of exposed components is limited and the complete electrical integration is performed in the

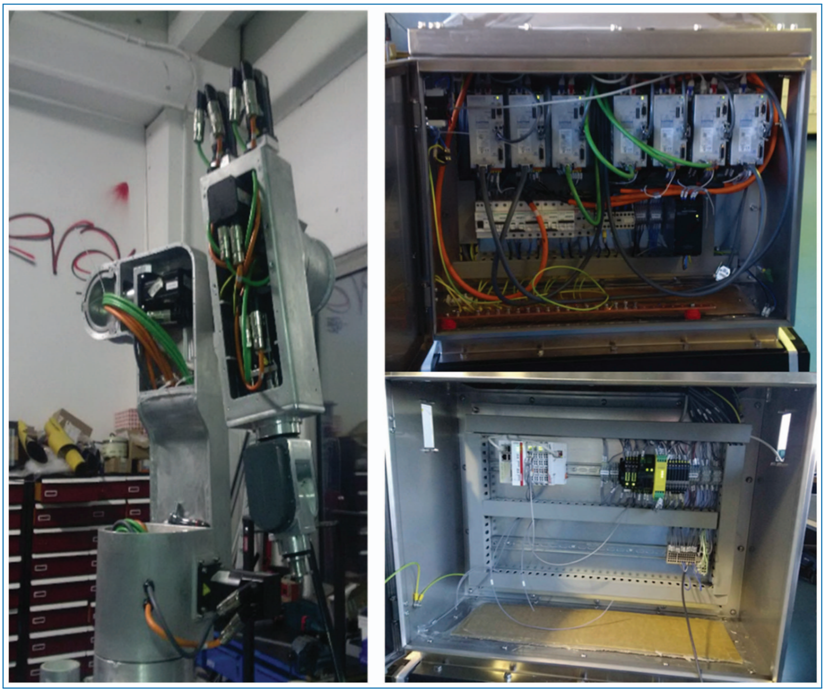


Figure 3.180. Robot arm integration (details).

robot supporting structure, leaving a significant free space for further modules integration. On the other hand, even if the low level joint control is completely different than the V1 prototype (different motors and different drivers) thanks to the adopted Ethercat protocol the new robot arm was seamless integrated on the upper control layer.

The main components of the Robotic Unit V2 system were shipped to the system integrator (Eurecat) facilities together with the system documentation (electrical and mechanical diagrams) and set up guidelines. Eurecat, supported by the different partners involved, proceeded with the full integration and assembly of the Robotic Unit V2. Learning from the past experiences and as an attempt to avoid the incurred delays and found problems with the Robot Unit V1, intense tests were conducted at the system integrators facilities to validate the continuous operation of the integrated Robot Unit V2. In this task, it was tested the electric, mechanical, communication and software interfaces between the arm, the two mobile platforms, the cable-reel unit, the external user-interface unit and all the sensors. Tests were also carried out of autonomous and manual navigation of the platforms in tandem formation and operating independently. The arm control was also tested in manual and autonomous mode, being able to move the tool from one position to

Figure 3.181. Robot arm integrated on the robotic platform.

another and to land softly on the wall. Besides, cable and hose pick-up and release tests were made, in manual and automatic mode (i.e. synchronized with the mobile platform movements). Once the whole robot was fully functional, it was sent to the RWTH facilities to perform grinding tests repeatedly and in different operational conditions, among other tests, to finally validate the robotic system.