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

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Summary:

This document provides a description of the final prototypes developed for navigation for the dual arm robot including visual docking modules. It describes the software developed for the prototypes for Standard SLAM Based navigation, 3D navigation, Static Docking and Mobile Docking.

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2. EXECUTIVE SUMMARY

The content of this document is the description of the final prototype of the navigation software for the THOMAS's dual arm MRP including the visual docking modules.

The main purpose of this document is to describe the status of the current system as it is implemented in the prototype. Thus, only a brief description of status and capabilities should be provided.

Technical advances already reported in previous deliverables will be shortly described and referenced to the related deliverable. This document goes into more detail in the following modules:

- Cell-to-cell navigation: 2d navigation improvements by 3d perception fusion.
- In-cell navigation: mobile docking: mobile reference accurate positioning and trajectory following.

3. INTRODUCTION

This document describes the final prototype of the modules composing the navigation software implemented in the THOMAS MRP (a dual arm mobile robot).

As stated in the proposal and in previous deliverables, navigation has been separated in two main tasks, which will be briefly described in Section 5:

- Cell-to-cell navigation (Section 5.1): When the MRP needs to move between different workstations along the workshop. The approach followed is that of using state of the art 2D navigation techniques, augmented with the fusion of 3D information provided by additional sensors.
- In-cell navigation (Section 5.2): When the MRP needs to move inside the workstation. The main purpose of this phase if for the MRP to be able to achieve enough positioning accuracy to be able to perform the required manipulation tasks. While standard approaches used in cell-to-cell navigation are good enough for obstacle avoidance and to approximately approach the desired position goal, it is not accurate enough for other tasks. Thus, a visual docking mechanism has been developed to accurately achieve a good final position. Moreover, the use cases include a scenario with a “mobile workstation” in which the MRP need to perform a screwing operation on the parts that a moving MPP is carrying. A mobile docking mechanism also has been developed to track and keep relative position with respect to a mobile goal.

The navigation prototype has been showcased in real live in two demos (Section 6). A public demonstration was made as part of the Open Doors day organised by the EU Robott-net project in the San Sebastian’s TECNALIA premises. The second occasion was the THOMAS integration workshop done at LMS, in which the in-cell navigation static and mobile docking was integrated into the LMS’s MRP.

Most of the development has been previously reported in prior deliverables. Thus, only an overall description of the systems and their capabilities will be provided. For more complete, technical descriptions, relevant previous documents will be referenced when required.

4. PERCEPTION ENABLED NAVIGATION AND DOCKING FOR MOBILE ROBOTS: FINAL PROTOTYPE

4.1. CELL TO CELL NAVIGATION

4.1.1. 2D NAVIGATION

Laser based SLAM navigation was successfully implemented in earlier versions of the prototype. The ROS based standard navigation package was adapted to be used with the MRP. Additional modules where developed to improve the system's efficiency and safety. The navigation system was composed of three modules:

- Laser based navigation. As mentioned, the standard ROS navigation stack was adapted to the sensors and dynamics of the MRP. After testing different algorithms for SLAM, localization and planning, the final configuration uses the following standard ROS packages:
    - SLAM: For creation of the environment map, the package *hector_mapping* is used. There was not much differences with the resulting map against the other candidate (*gmapping* package), but it was chosen as a more robust solution since it doesn't depend on an external odometry source.
    - Localization: For map-based localization, the well know, robust and widely used Augmented Monte-Carlo Localization (AMCL) package was used.
    - Planning: For global planification, the purely geometric *global_planner* package was used, as the de facto standard planner in the ROS navigation stack. Local planner was more critical selection, since it must be able to properly adapt the specific dynamics of the platform and be able to be tuned for a specific behavior. After extensive testing and parameter fine tuning, the Timed Elastic Band (*teb_local_planner*) package was chosen.
- Low level wheel management: THOMAS MRP uses the Swerve Drive locomotion configuration. The MRP's controller was modified and fine-tuned to provide the smoothest movement possible, avoiding wheel reconfigurations as much as possible.
- Dynamic robot footprint: Navigation planners require to know the robot's own "footprint" (that is, the space it occupies in an environment) to know if it will collide or not with other elements in the environment. In 2D navigation, this is typically done by projecting the plant of the robot to the ground. However, as the MRP has mobile parts (the arms), this footprint can change over time, depending on the configuration of the arms. To avoid this problem, it was developed a module that keeps track of the robot arms' joints and accordingly updates the footprint. Also, the planner was modified to be able to work with dynamic footprints.

A more detailed description of these modules can be found in deliverable 3.4 "Perception enabled navigation and docking for mobile robots: Initial Prototype"

4.1.2. 2D NAVIGATION IMPROVEMENTS BY 3D PERCEPTION FUSION

2D laser-based navigation is the current state-of-the-art navigation approach for indoor structured environments. The use of the "plant" of the environment as a map is a well know, widely used and robust method for localization and navigation. It has, however, some also well know limitations, like its sensitivity to ambiguity in very symmetric environments.

Safety wise, there is one critical issue that arises by the same nature of the environment representation that the system uses. The "known world" is limited to what the robot's sensors can see and can be represented in the map. In the typical laser-based navigation, this is limited to obstacles in a plane at the height at which the laser scanners are mounted. This causes that obstacles above and below this plane are invisible to the robot.

In a typical structured environment, most of the existing obstacles do not suppose a threat, since they typically have flat vertical surfaces and go from the ground to some height. So, a low mounted laser can safely detect most of them. However, protruding and hanging obstacles, tables or very low obstacles

like pallets still possess a safety threat. One typical and especially dangerous case are the feet, since they easily can project 20-30 cm from the leg (that will be what the robot actually detects) and can be overrun even when the robot has detected the person, depending on the robot's safety configuration.

A full 3D localization/navigation system should be able to overcome these problems. However, current state of 3D navigation is not so developed and well tested as 2D navigation, so any intent of using such technology will require longer development times with much more uncertain results. Alternatively, standard 2D navigation can greatly benefit from the use of 3D information sources, while retaining its well know robustness.

This approach is the one followed in THOMAS: to improve 2D navigation by 3D perception fusion, using 3D cameras to feed relevant 3D information to the navigation system.

3D perception source

Multiple possibilities exist for providing 3D information for use in the navigation, both onboard and offboard the MRP. The MRP is already equipped with several 3D able cameras, like the RC_Visard cameras from Roboception. These cameras, however, require a pattern to be projected to be able to get 3D information, so they were discarded for navigation purposes as they would require the projector to be constantly lit.

Alternatively, an Intel RealSense D435 3D camera was mounted in the prototype for testing purposes.

As the vertical field of view of the camera is limited, how the camera is mounted in the MRP is relevant to its usefulness for obstacle detection. Basically, three options were possible:

- Horizontal mounting: This would be the most standard mounting (Figure 1). However, due its limited field of view the camera would only detect obstacles far away from the robot. That will limit its usefulness, since, while the detected obstacles would be used for global navigation, only close obstacles are relevant in the local navigation and are more relevant for safety.

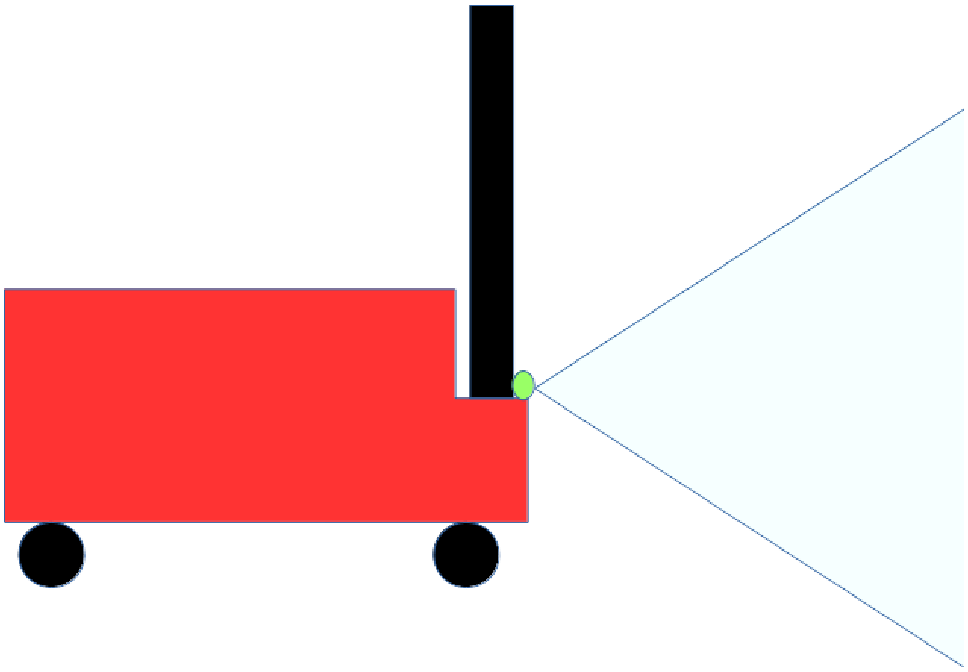

Figure 1: Front facing mounting

- Tilted mounting at low height: A camera mounted this way would be able to detect close-by obstacles at all the height of the robot (Figure 2). However, it has the same problem than the lasers, as it would not be able to detect very low obstacles.

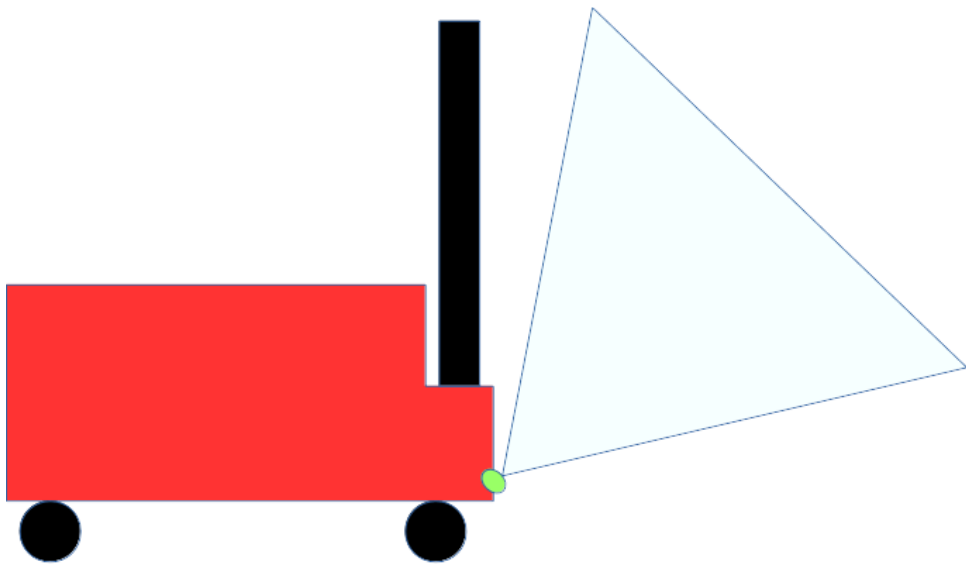

Figure 2: Bottom-up facing mounting

- Tilted mounting at high height: It can detect close-by obstacles from its mounting point to the ground (Figure 3). Available mounting points in MRP are high, so it was considered that this mounting would be the one with greatest obstacle detection capabilities.

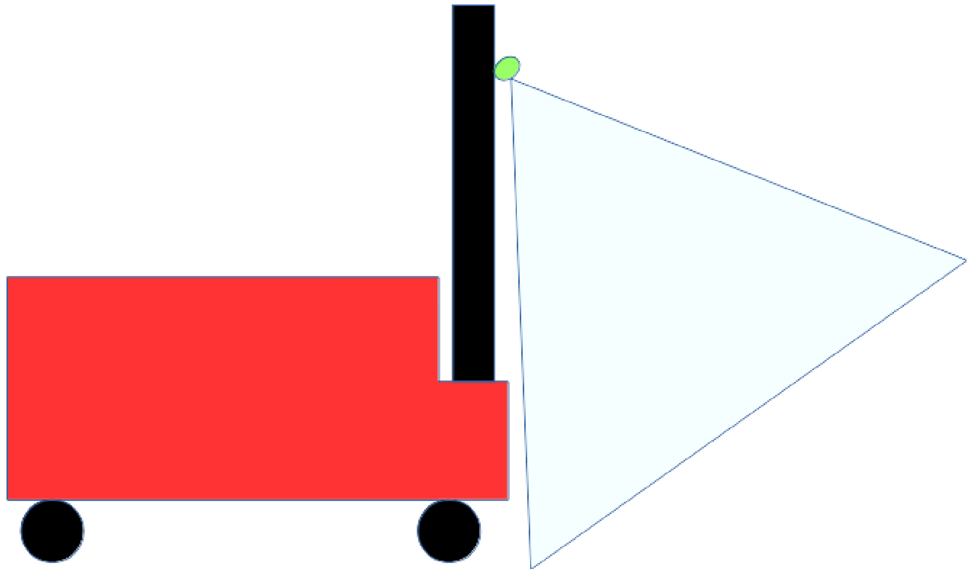

Figure 3: Top-down facing mounting

Final mounting was done in the auxiliary plate between the two dual arms in the MRP's torso, pointing down 60º degrees, as shown in Figure 4. The camera was manually calibrated so the acquired point cloud was properly acquired with respect of the robot. The ground was removed from the point cloud up to a height of 1 cm.

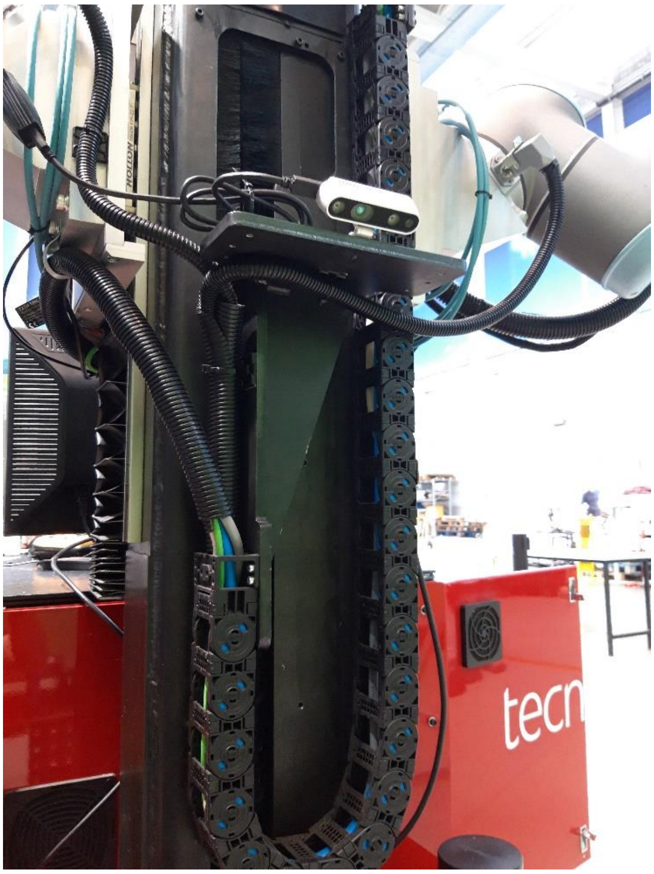

Figure 4: Final mount point of the RealSense camera

It needs to be considered that a single front-mounted camera has limited functionality in an omnidirectional platform for navigation purposes. It will only be able to detect obstacles in front of the robot, whereas the robot can, and usually will, move backwards and sideways. As it is done with the laser scanners, a fully practical installation will require multiple cameras covering 360º around the robot. On the MRP prototype only one camera is being used for testing purposes.

3D obstacle detection

The 3D information (point cloud) provided by the 3D camera is used for detection of 3D obstacles.

The point cloud feeds a new layer in the costmap (occupancy grid) used by the navigation. In this layer, instead of using a single, planar cell to represent each map position, a column of voxels is defined. If the position of points in the cloud fall within the voxel, the voxel is marked as occupied. Then, this voxel column is flattened, giving the highest occupation value in the voxel column to the corresponding cell in the navigation map. In this way, any position in the map will be marked as occupied even if the obstacle occupying it is above or below of the plane of the laser scanners.

Once the costmap is updated with the 3D sensor information, this information is seamlessly used by the navigation stack, thus allowing the robot to avoid previously invisible obstacles.

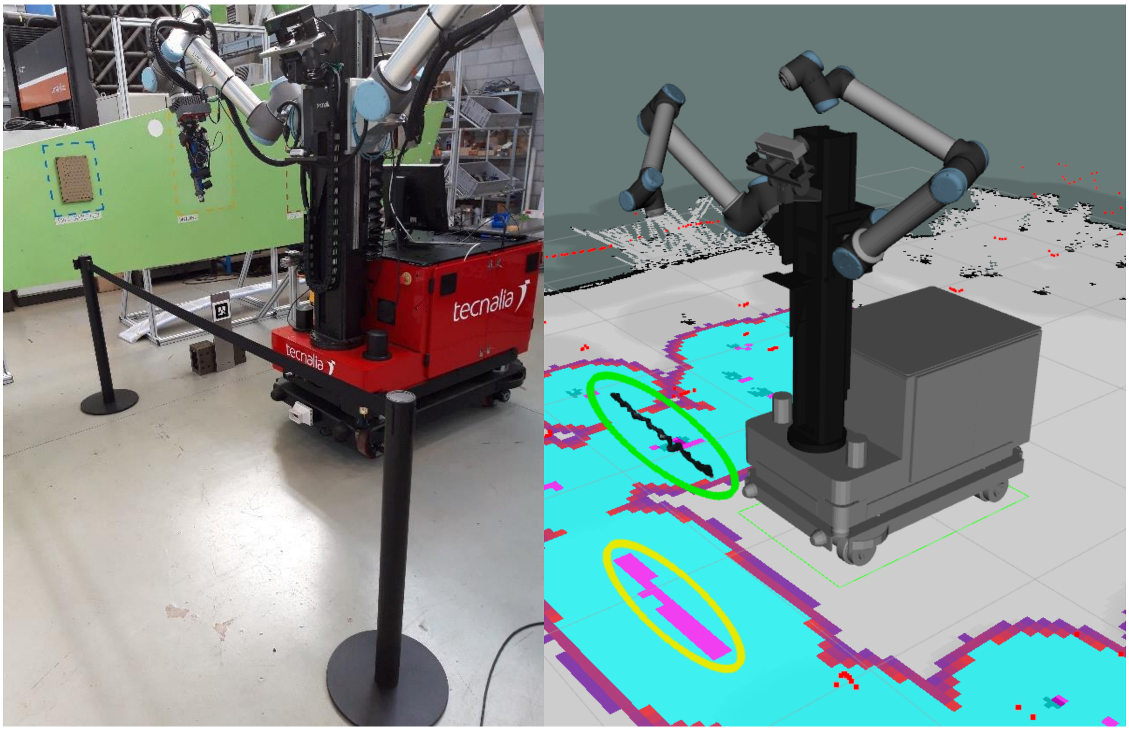

Figure 5: Obstacle above the laser's plane detected and projected to the obstacle map

4.2. IN-CELL NAVIGATION

4.2.1. STATIC DOCKING: ACCURATE POSSITIONING WITH RESPECT TO A STATIC REFERENCE

Drilling, sanding and some manipulation tasks require a constant flow of compressed air. The MRP's internal compressor is only able to provide enough air pressure flow a few seconds. Thus, it was required that the MPR must attach itself to a docking station that will provide this airflow. This docking procedure required high positioning accuracy, which would also be required by the operations themselves (drilling pattern detection, self-positioning against the wing in sanding processes, etc).

As described in deliverable 3.4, a docking module was developed. An AR marker was used to self-locate with respect of a pre-calibrated relative position. Estimated relative position of the marker was translated to control movements. Also, additional safety measures were introduced (e.g. limiting speed depending on distance to laser detected obstacles).

The developed system has proved to be robust, being able to achieve docking successfully from almost any position, given that the marker is in the field of view of the docking camera. The only drawback found was, being a vision-based system, a sensitivity to extreme lighting conditions.

Given its robustness, the system is already being used in other projects with applications with similar relative positioning needs, like the EU Versatile project.

4.2.2. MOBILE DOCKING: MOBILE REFERENCE ACCURATE POSITIONING AND TRAJECTORY FOLLOWING

In-cell navigation in the PSA use case requires the synchronized navigation of the MPP and MRP. While the developed static docking is robust and accurate, it is not designed to track and follow a moving target. Thus, a different system was required for this task.

Perception

In early approaches to the problem, as reported in deliverable 3.4, a sensor fusion system using the on-board Microsoft Kinect and the laser scanners where proposed. This approach tried to combine the accuracy of the marker-based tracking with the speed of laser scanners.

Initial tests, however, showed that the head, pan-tilt mounted Kinect camera was not accurate enough for the task, due the big minimum distance to the target marker, low camera resolution and difficult calibration of the kinematic chain encompassing the robot's base, torso and pan-tilt unit.

Similarly to the final configuration of the static docking, an industrial IDS uEye GigE camera was mounted on the robot's side at low high. This mounting point allowed to place the tracking marker on one of the "legs" of the MPP's dolly where it both allowed a very close tracking distance (~50 cm.) a good position of the torso and arms over the dolly for manipulation tasks.

Figure 6: Mount points of the marker (MPP) and tracking camera (MRP)

The fixed mount, high resolution and close tracking distance provided very good tracking accuracy. Moreover, the camera and tracking system were able to provide up to 30 fps. This speed made unnecessary the fusion of lasers for increased tracking speed.

Control

As the goal of the application is to be able to perform some manipulation in the parts carried by the MPP's dolly, the target of the tracking system is to maintain formation with the MPP. As the union between the MPP and the dolly is not rigid, a steady relative position to the dolly (and not the MPP) should be kept.

While the MPP's movement is linear in most of its trajectory, dolly's movement is more erratic, oscillating depending on different variables like initial position of the wheels or the conditions of the ground.

Thus, control of the MRP should be done in the three possible degrees of freedom: lineal, lateral and angular speeds. Since dolly's movements in each dimension were expected to be very different, each speed component was controlled with its own PID with different gains. This way, for instance, linear PID had much higher reactivity than lateral or angular ones.

PID were fine-tuned by repetitive testing in TECNALIA's San Sebastian premises, using an MPP ceded by PSA.

Figure 7: MPP-MRP dynamic docking test at TECNALIA's workshop

Achieved accuracy was in the order of < 1 cm. once the following stabilizes, which takes approximately two seconds. This error should be mechanically absorbed easily by the arms or tooling.

However, at the start the error can get as high as 6 cm. This initial high error is inherent to the reactive nature of the feedforward PID and the dynamic reactions of the MRP (command to action delays, acceleration ramps, etc.). The initial error can potentially be greatly reduced if the system is able to command both the MPP and MRP to start simultaneously, instead of the MRP to be waiting for the MPP to start moving (Figure 8). Unfortunately, this capacity required of some equipment from the AGV provider that was not available at the time of development. If available, it should be tested as part of the integrated demonstrator.

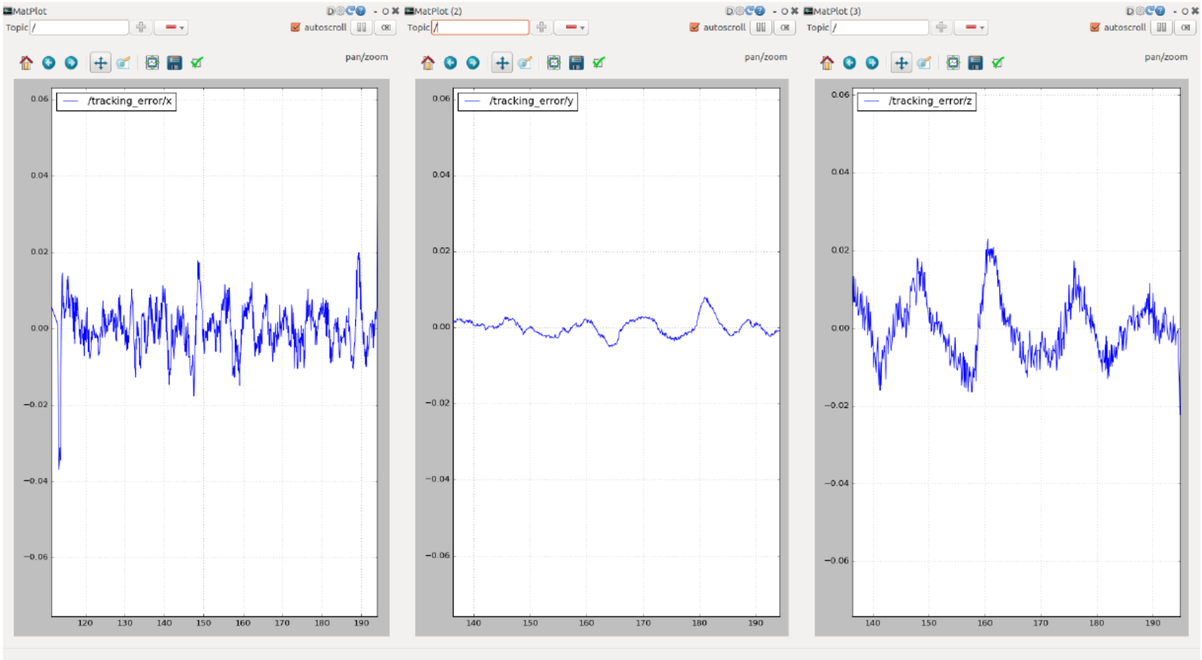

Figure 8: Tracking error in each axis (X,Y,Yaw) for a sample run of the MPP-MRP dynamic docking

5. PROTOTYPE DEMONSTRATIONS

5.1. ROBOTT-NET Training Event

ROBOTT-NET is an ongoing EU project devoted to assuring that technology developed by the European RTOs through EU funding is successfully transferred to commercial companies.

One of the activities that ROBOTT-NET organizes are Training Events. These are “open doors” days in the consortium RTO’s premises in which companies are invited to visit the RTO’s installations and their technology developments are presented.

On 26th of February 2019, a Training Event was held at TECNALIA’s premises in San Sebastian. Along with other ongoing projects and developments, the current prototype of the THOMAS system was shown performing a reduced demo of the project’s use cases.

The MRP performed drilling, navigation and static and dynamic docking demos.

Figure 9: THOMAS demo at ROBOTT-NET Training Event at TECNALIA’s San Sebastian premises

5.2. LMS Integration Workshop

From 12th to 15th of March 2019, an integration workshop was held at LMS’s premises. This integration workshop was used to successfully transfer the static and dynamic docking modules from TECNALIA’s MRP to LMS’s MRP.

The docking modules required slight modifications to cope with hardware differences between the two versions of the MRP, but both static and dynamic docking (following the real MPP) were successfully demonstrated.

In Figure 10 a co-navigation between the MPP and LMS’s MRP at LMS’s workshop is shown. It can be appreciated how the MRP is following the MPP backwards, due the fact that the tracking camera on the LMS’s MRP was mounted on the opposite side than TECNALIA’s MRP.

Figure 10: MPP-MRP dynamic docking test in LMS's workshop

6. CONCLUSIONS

This document shows the state of the final prototype of the MRP's navigation system, ready for integration in the use case demonstrators. Wille fully functional, further development and improvements are expected during the demonstrator preparation phase.

The current systems navigation capabilities and robustness has been demonstrated in several demos. 2D navigation has been improved by the fusion of 3D sensors information that allows for detection of obstacles beyond the plane of the laser scanner, improving system's safety. Also, both static and dynamic docking are performing robustly, with only some problem found in extreme lighting conditions.

Further developments will be related with the integration of the systems in the full-scale use case demonstrator.

- In cell-to-cell navigation, only few tweaks are expected to be needed and most development will be devoted to integration of new sources of sensor information (off board sensors, world model).
- In in-cell navigation, most of the required work is expected to be done in the dynamic docking, trying to improve as much as possible its accuracy, in conjunction with the screwing process.

7. GLOSSARY

MRP	Mobile Robot Platform
MPP	Mobile Product Platform
SLAM	Simultaneous Localization And Mapping
AMCL	Augmented Monte-Carlo Localization
Swerve Drive	Full 2D drive train in which all wheels are steered.
ROS	Robot Operating System
AGV	Automated Guided Vehicle
PID	Proportional Integral Derivative