A robotized dumper for debris removal in tunnels under construction

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Abstract. Tunnels in construction exhibit many challenges for automation. In this work we address the robotization of a conventional dumper for debris removal during the construction of tunnels, in the framework of a technological transfer project. The goal is to convert a dumper into an autonomous vehicle capable of planning, navigate and localize itself. Planning and navigation techniques have been adapted to the special kinodynamic characteristics of the vehicle. The difficulties for having a precise continuous localization in this kind of scenarios, due to the irregularities of the terrain, the changing illumination and the own scenario, have driven to develop hybrid localization techniques to integrate continuous and discrete information, coming from the navigation sensors, some semantic geometric features, and the signal strength propagation in tunnel scenarios. Simulation and real-world experiments are described, and some preliminary results are discussed.

Keywords: Tunnel. Dumper. Autonomous navigation. Challenging scenario.

1 Introduction

The construction of infrastructures (roads, railways, hydraulic infrastructures, etc.) faces the challenge of avoiding multiple orographic accidents, with tunneling being a frequent solution in many of these cases. Underground construction in general and the excavation of tunnels in particular, are subject to an inherent risk to their own activity. Of course these types of works are carried out with intense campaigns and geological studies, well-designed support measures and high precautions and safety protocols. Unfortunately, this does not prevent occasional accidents from happening. Although the frequency of such accidents is low, the consequences are unfortunately often fatal.

AUTODUMP[4] is a ongoing technological transfer project, whose partners are the Robotics Research Group of the University of Zaragoza, the Technological Institute of Aragon (ITAINNOVA), the spanish manufacturers association

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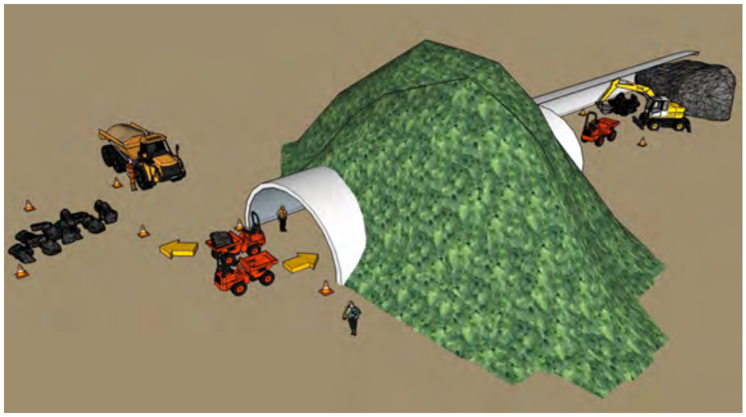


Fig. 1: Overview of the process. The dumper navigates autonomously through the tunnel until the beginning of the excavation. Then, the debris is deposited in the bucket and the vehicle goes outside the tunnel.

of construction and mining equipment (ANMOPYC), VIAS Y CONSTRUCCIONES company as a final user, and the collaboration of General de Alquiler de Maquinaria (GAM). It aims to eliminate these risks by reducing the presence of people in the stage of debris removal in tunnels. It is important to emphasize that the debris removal is carried out after the blasting and before the execution of the support that supports the vault of the tunnel, reason why it is one of the critical moments in the construction of tunnel with the Austrian method [3]. A conventional dumper has been robotized, providing all the functionalities for autonomous navigation. For reasons of confidentiality we cannot detail some techniques used, but we want to transmit the difficulties and challenges found, and some solutions to cope with them.

That is why the overall objective of this project is the design, development, manufacturing and validation of a robotization kit that allows to transform a conventional dumper into a self-propelled mobile robot capable of reaching the excavation front without human intervention, waiting to be loaded and then transporting the debris generated at the excavation front to the outside the tunnel where it is unloaded. Figure 1 summarizes the process that is repeated during the working day.

Several challenges appear from the viewpoint of the autonomous navigation. All of them are related to the especial characteristics in this kind of environments (see Fig. 2(a)):

- The terrain is irregular, full of potholes, puddles, and mud. The walls are also irregular during the construction time.
- Other vehicles and people are walking in the scenario in which the work continues.
- The illumination is poor and changing, the latter due to other vehicles moving around.
- The scenario is changing because the own nature of the work, the front of the excavation advances. Neither a pre-built map exist nor can be easily made.

(a) (b)

Fig. 2: Tunnel in construction (a) inside, (b) outside

All these characteristics make the scenario very challenging for navigation and localization.

2 Robots and scenarios

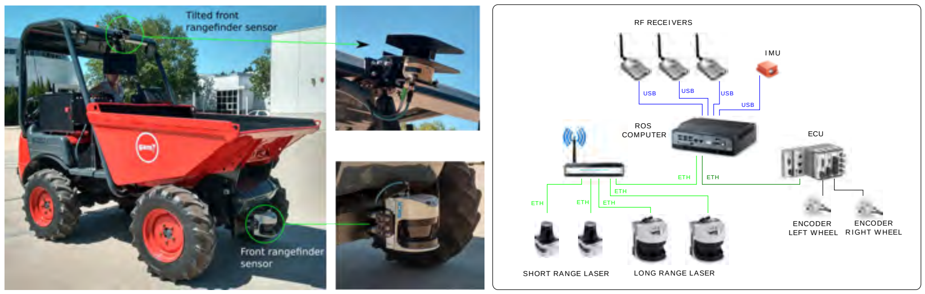
The final goal of the project is to robotize a standard commercial dumper commonly used in debris removal tasks and to test it in a actual under-construction tunnel. However, the preliminary real-world experiments have been performed with another robotic platform in the Somport tunnel. In the next sections we present the robots and the settings involved in the project.

2.1 The ITAINNOVA robotized dumper

The robotized dumper is shown in Fig. 3. It is composed of various electrical, electronic, mechanical or hydraulic elements, capable of acting on the original systems of the conventional dumper. It also can be driven manually. The dumper has an automatic steering system capable of acting on the original steering system of the dumper, an automatic traction system capable of controlling the speed of the dumper, and an automatic braking system capable of reducing the speed of the dumper and stopping it completely.

All these systems are controlled by an Electronic Control Unit (ECU), shown in Fig. 3(b). This ECU reads the actual velocity and steering angle of the vehicle and is able to command the automated systems of traction and steering to reach the desired values of linear velocity and steering angle. In order to do that, it has been necessary to install an odometry system composed by two encoders on the front wheels to estimate the velocity of the vehicle, and a potentiometer sensor on the steering wheels to measure the steering angle. Thanks to the odometry system mounted on the front wheels it is also possible to estimate the position and orientation variation of the prototype.

Several sensors have been installed for autonomous navigation. Four rangefinder SICK sensors, two in the frontal part (see Fig. 3(a)) and two in the rear part



(a) (b)

Fig. 3: The ITAINNOVA robotized dumper. Front part of the vehicle (a). Dumper hardware and communications architecture (b).

which allow forward and backward navigation. They all are needed because manoeuvrability inside the tunnel could be not possible many times, due to obstacles, other vehicles, or narrow ways. Thus, both modes of navigation have to be implemented. The two rangefinders on the roof of the vehicle have been installed tilted, heading the floor, to scan the imperfections and irregularities of the ground. Furthermore, an Inertial Measurement Unit (IMU) has been installed on the chassis of the vehicle to fulfill two tasks. On the one hand, the 3D orientation provided by this sensor will be used to compensate the rangefinders information, that can be misleading when the vehicle goes through irregular terrain. On the other hand, the data generated by the IMU will be fused with other sources to improve the pose estimation of the prototype.

The last part of the robotization kit is an industrial computer, where all the localization, obstacle detection and navigation algorithms will be executed. Its operating system is Ubuntu 14.04 LTS and all the algorithms have been developed to run under ROS Indigo distribution. An overall scheme of robotization kit is shown in Fig. 3(b).

2.2 Preliminary experiments setup

Developing such a complex platform is not an easy task. For this reason, a Robucar-TT belonging to the Robotics Group of the University of Zaragoza has been used for developing the preliminary experiments (see Fig. 4(a). It is equipped with two frontal and two rear lidar SICK sensors, two in a horizontal orientation to detect obstacles in front and behind the robot and two tilted to detect the irregularities of the terrain, cameras, and several communication systems.

The preliminary scenario was chosen to be the out-of-service Somport railway tunnel (see Fig. 4(b)). This is a 7.7 km straight tunnel that connects Spain and France through the central Pyrenees. It has a horseshoe-shape cross section, approximately 5 m high and 4.65 m wide (see Fig. 4). It also has small emergency shelters every 25 m (which are 1 m wide, 1.5 m high, and 0.6 m in depth), and 17 lateral galleries, each of them of more than 100 m and of the same height as the tunnel.

(a) (b)

Fig. 4: (a) Robucar-TT front view, (b) Somport tunnel and a rear view of the Robucar-TT equipped with 2 SICK lasers

3 Navigating in tunnels

As explained before, deploying an autonomous robot in a challenging environment requires taking into account several aspects like localization and navigation. However, even state-of-the art solutions are not always fit in the described scenarios. On the one hand, neither a pre-built map is obviously available nor it is useful to build one given the changing nature of the scenario. On the other hand, the presence of mud, irregular illumination, etc. invalidates most of the well established techniques for localization and navigation.

3.1 Localization in the tunnel

Global localization and planning in large and few textured environments are challenging. Using exclusively geometric-based SLAM techniques for continuous localization and mapping might lead to high localization uncertainty after travelling during long periods of time [10]. Also, as said in section 1, illumination is poor and changing; this makes visual-SLAM methods —that work correctly in textured and well illuminated scenarios— fail in these scenarios. Moreover, in many already finished tunnel sections the walls are flat, without texture and features that would allow the self-localization of the dumper. In this case, classical geometric scan matching or SLAM techniques based on dense or semi-dense geometric information —either using vision or rangefinder sensors— do not work, either.

The impossibility of using an absolute localization with the necessary precision makes the subsequent navigation a complex task. However, the predictable structure of the tunnels can provide local information that can be sufficient for a successful localization.

The sections that are under construction are characterized by walls that have marked roughness, that are suitable for extracting features that allow the dumper to estimate its position with sufficient precision.

Instead, in finished sections the walls do not have these characteristics but the parallel and smooth walls offer useful information that can be used to perform an effective transverse ($y-$axis) localization. On the other hand, an exact longitudinal ($x-$axis) localization is not always necessary; it is sufficient to know when the robot needs to stop at the beginning or at the end of the tunnel for loading or unloading the burden.

Continuous localization with geometric features. As anticipated, in the finished stretches of the tunnel, the parallel smooth walls are used to localize the vehicle in the $y-$axis: the longitudinal axis of the tunnel is considered to have coordinate $(x, 0)$ with $x \in [0, L_{max}]$ being L_{max} the length of the tunnel. In other words, a made-up reference frame is built, in which the tunnel walls identify the axes being the instantaneous central axis of the tunnel the $x-$axis. To establish the y and θ position of the robot in this reference, a simple technique based on the Hough transform is used. The readings of the available rangefinder are processed extracting the lines present in the scene. These are filtered and the two of them that represents the walls are used to obtain the information being sought.

The x position is instead conveniently obtained by integrating the measurements of different sources of information provided by on-board sensors —such as the odometry and IMU— as well as the features of the environment.

When the robot reaches the under-construction part of the tunnel —which is usually plenty of features—, standard scan-matching-based techniques can be used. These offer a good precision in short stretches and textured scenarios even if, as is well known, accumulate error over the time in few textured ones, especially in the longitudinal axis.

Notice that the localization is continuous and seamless in the sense that there is not a switch between the two methods of localization but all the measurement are integrated by means of an EKF filter taking into account the uncertainty provided by the different sources at any moment and maintaining the reference frame defined by the tunnel walls.

Improving localization with semantic features. All odometry, IMU and scan-matching based techniques are well known to accumulate error over time.

To reduce such error, we developed two techniques to provide absolute positioning and reduce the accumulated error. The first of them is based on semantic features recognition (SFR), while the second rely on the specific characteristics the RF propagation has in waveguide-like environments, like tunnels. When these measurements are available, they are integrated in the cited EKF with the end of resetting the error.

The SFR consists in recognizing special natural features in the scenario; by construction, a tunnel usually have main gallery, which is long, straight or slightly curved, but also lateral galleries located every given number of meters, or easily-recognizable dead-ends. Just to give an example Fig. 5 shows the small

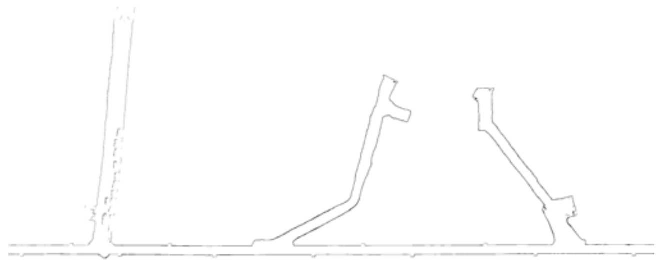


Fig. 5: The semantic features learned by the system are *left/right_gallery*, *+_cross*, *T_intersection*, *end_gallery*. In the figure three *left_gallery* from the main gallery, and several *end_gallery* can be seen. They allows to manage a topological-semantic map based on these features, making available a discrete localization.

part of the Somport tunnel used in preliminary experiments with some relevant features that can be recognized by the SFR.

A key to overcome the localization problem is to use these features to compute an absolute $x-$axis position when a semantic feature is recognized and provide it as an absolute measurement (if the actual position is known). Even if a centimeter accuracy is not achievable, this can help to reduce the error accumulated during the continuous localization.

The main challenge is the correct recognition of the features. We have developed a technique for learning and recognizing those features. They are computed from the raw information provided by a 2D laser rangefinder sensor, but could also be applied to information computed from 3D range or RGBD sensors. The method first performs an input space (laser scans) transformation based on *Principal Component Analysis* (PCA), and then a *Linear Discriminant Analysis* (LDA). This process captures the main characteristics of the features and reduces the information in order to obtain a clear and robust discrimination. Once the input space has been transformed, a bayesian classification scheme is applied in order to recognize the features. The detailed algorithm, that has been successfully used in [9], can be found in [8].

Radio-frequency landmarks. Another information that can be integrated and that is one of the main research contribution in this project, is to use the communication signal strength to compute an absolute localization inside the tunnel.

Wireless propagation in tunnel-like environment differs from regular indoor and outdoor scenarios. Previous studies performed in tunnels demonstrate that the communication range can be extended in comparison to free space, but the signal suffers from strong fading phenomena. However, it is possible to obtain known periodic fadings under certain transmitter-receiver configurations (see [6]).

The main goal is then to take advantage of this periodic nature of the RF signal in order to correct the accumulated error from other sensors, such as odometers. As a first approach, the detection of the fading minima allows to correct the position of the robot periodically (as was proposed in [7]). The dis-

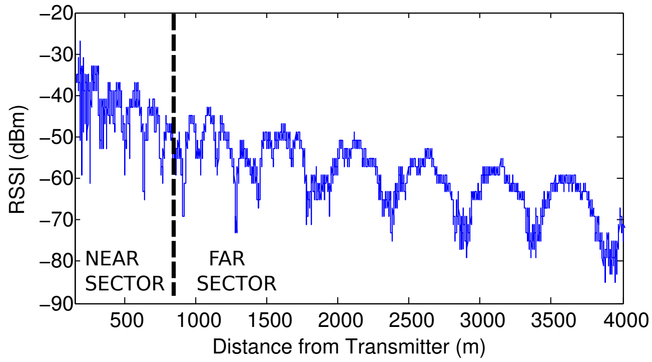


Fig. 6: Measured Received Power at 2.4 GHz inside the Somport tunnel, from [5]

tinguishable features of the RF signal would play the same role as the lateral galleries. Figure 6 shows the fadings waveform in the Somport tunnel at 2.4 GHz.

Artificial landmarks. Finally, another of the external elements used for localization are the reflective beacons located in the tunnel. The detection of these beacons is done by means of the laser sensors onboard. The detection is based on the reflective property of the beacons material. As these elements will be located at characteristic points of the tunnel (area of debris, tunnel entrance, excavation front), the detection of these elements will enable estimation of the position with respect to the tunnel.

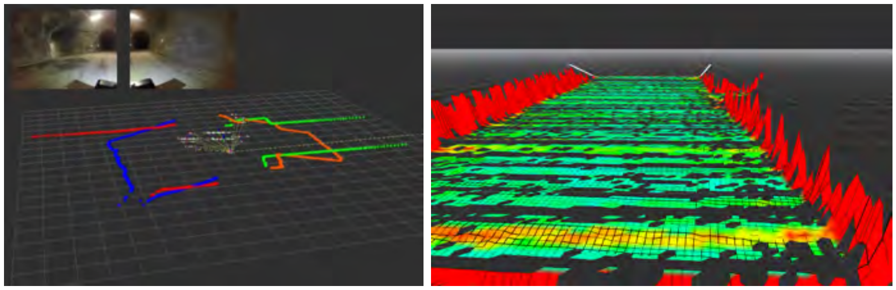
3.2 Autonomous Navigation

The autonomous navigation of a platform in a changing environment such as a tunnel under construction, is limited by several factors. On the one hand, there is no pre-built map of the environment to explore since this environment is being built while the platform is navigating. On the other hand, as mentioned in the previous section, the localization could not be as precise as it would be desirable.

However, the described localization techniques allow an effective autonomous navigation. Given that the walls allow the identification of a frame whose $x-$axis overlaps the longitudinal axis of the tunnel, a navigation goal with coordinates $(5, 0)$, for example, will make the robot move forward and stop five meters ahead, just in the center of the tunnel. Being always localized with respect to the longitudinal axis simplifies the navigation algorithm especially considering that robots must only move back and forth along the tunnel.

Naturally, the navigation must include an obstacle avoidance system. This has been implemented using a hierarchical system composed of a global and a local planner. The latter is in charge of reaching the halfway goals provided by the global planner avoiding obstacles, while the first computes a viable trajectory toward a global goal.

We tested several local planner and find out that the best options are a slightly modified version of the simple Dynamic Window implementation [2]



(a) (b)

Fig. 7: Terrain information for navigation. Readings of the four lidar sensors (a). Elevation map (b).

and of the Obstacle Restriction Method (ORM) [4]; due to the nature of the environment, the navigation must be reversible without any maneuvering of the platform that must be able to go forward and backward. Both algorithms has been adapted to fulfill this requirement.

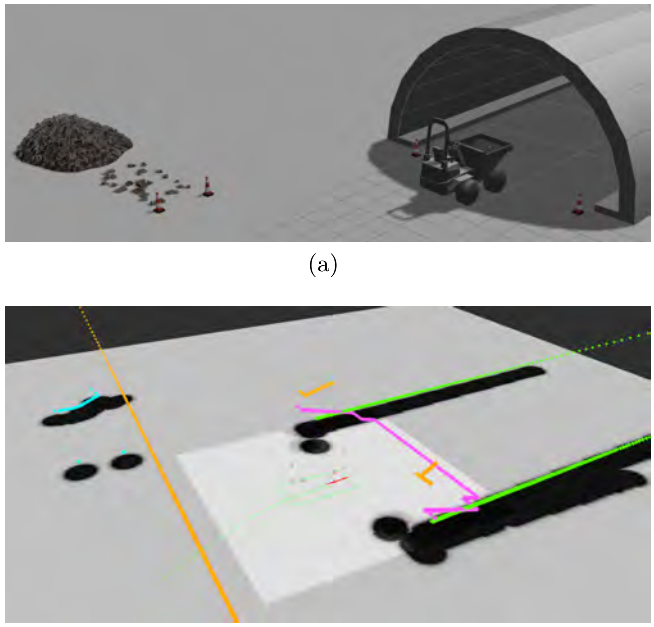
On the other hand, given that under-construction tunnels have an irregular terrain with potholes, puddles, mud, and static and moving obstacles, the global planner must take these into account when it computes the trajectory. To make that possible, a labeled local costmap including information about these features is needed. Elevation maps [1] to localize navigable and non-navigable areas are used. In Fig. 7(a) it can be seen the terrain information captured by the four laser rangefinder, two in the frontal part and two in the rear part of the Robucar-TT robot in the Somport tunnel. Figure 7(b) depicts the elevation map in an area of the tunnel, representing the terrain irregularities and the lateral obstacles (walls).

4 Experimental results

The project is in the final year, so there are not final results yet. Several experiments, in simulation and in real-world scenarios have been performed. Planning and navigation techniques have been adapted and implemented for the especial kinodynamic characteristics of the robotized dumper relying on the ROS middleware. They have been tested in simulation, using artificially built scenarios having the above mentioned features in tunnels being constructed. In this stage of the project the real-world scenario and robot described in section 2.2 have been used for obtaining preliminary results.

4.1 Simulations

Two main tasks have been performed in order to create a realistic simulation of the debris transport in tunnel construction process. The first one was the design and implementation of an accurate model of the vehicle. All kinematic and geometric details of the actual vehicle have been taking into account in



(a)

(b)

Fig. 8: Simulation environment. Simulated workplace on Gazebo (a). Sensors data generated by the simulator shown in Rviz (b).

order to test the performance of navigation algorithms correctly. The second one was the modelling of the workplace. In this case three main components were considered: the tunnel, the reflective beacons that indicate the key points of the process, and the debris pile. All the mentioned elements are shown in Fig.8(a). Additionally, the vehicle model includes all the sensors installed on the actual prototype, replicating its positions and orientations, as well as its technical characteristics. The data generated by Gazebo, the simulator used in this project, are shown in Fig.8(b). One of the main advantages of using Gazebo as robotic simulator is that the sensor data provided by the simulator has the same format and uses the same communication protocol as the sensors of the actual robot. So the gap between a simulated environment and the real world is closer than ever. In this way, the same architecture of processes designed using the simulator can be directly applied to the prototype.

During the development of Autodump project, the simulation has allowed to test a wide variety of navigation strategies, different sensor positions and orientations, as well as checking different parameters setup of the prototype, all of that without the difficulties related to the set up of the real vehicle. In this connection, it is remarkable how the simulation phase has made easier the deployment of the real prototype.

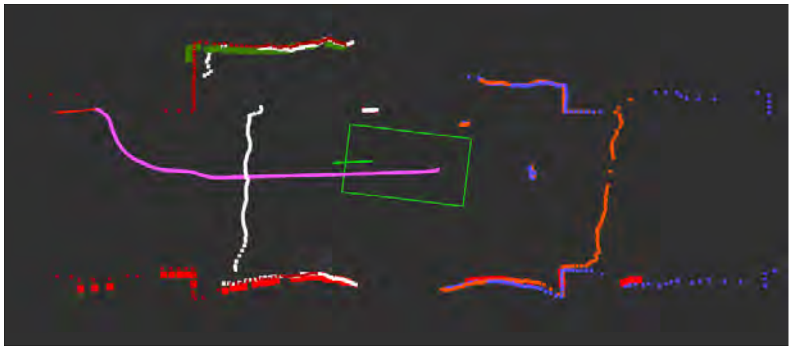


Fig. 9: Red, white, blue and orange points represent the laser information from front, front ground, back and back ground respectively. Green and red squares represent the lines extracted from the wall, and the red arrow in the goal computed with its path in pink.

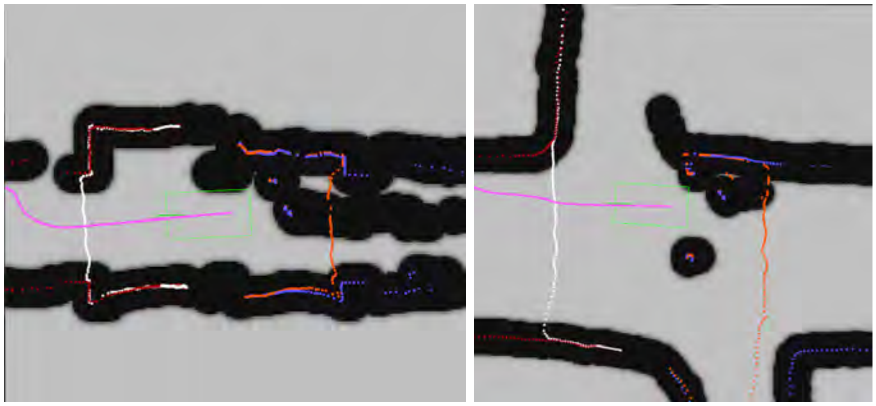
4.2 Real-world experiments

The first tests to evaluate the system were carried out in the Somport tunnel with the Robucar-TT platform. In this experiment we tested the localization and navigation techniques that would be used in the finished part of the tunnel. In this experiment the $y-$axis position was obtained using the Hough transform as described, while the longitudinal position through the integration of odometry and IMU readings. At the same time, we logged the radio signal strength received from an emitter located at the beginning of the tunnel in order to collect data to test the absolute localization based on RF landmarks.

In Fig. 9 it is possible to see the information provided by the sensors during the navigation. White and orange points represent the front and rear laser that point to the ground. Red and blue points are the information provided by front and rear laser. Using the technique presented in section 3.1 a set of lines are extracted (green and red squares in Fig. 9) from the laser information and give a raw representation of the wall (left and right wall, respectively). Using the reference obtained from these lines we assign the goal for the platform, in our case 3 meters to the left of the right wall. As we mentioned in the previous section, the navigation is based on a local map built using the sensor range information. Once the goal is assigned the global planner computes a path for navigation (pink line) is computed taking into account the local map of the robot. The green arrow represents the instantaneous direction chosen by the ORM local planner to reach one of the local goals provided by the global planner along the pink path.

Figure 10 shows the costmap created in two scenarios during the navigation. The left one shows the main corridor and some mobile obstacles behind the platform. The right one shows the local map when it is crossing a lateral gallery. In both snapshots we can see how the path computed try to perform a navigation close to the wall. A full video of one of the experiments can seen in [5].

[5] http://robots.unizar.es/data/videos/robot17Autodump.mpeg



(a) (b)

Fig. 10: Cost map. Platform navigating through the main gallery (a). Platform crossing a lateral gallery (b).

Figure 11 shows the results of the RF measuring campaign; it is possible to identify several fadings with a period of about 500 meters which is consistent with other measuring campaign performed in the past. With these readings and a proper analysis of the data it would be possible to reduce the accumulated error when no better estimations are available. If a better RF estimation is needed, different emitters can be positioned along the tunnel in a way in which the relationship among the partially overlapped fadings generated by the different emitters would allow the reduction of the uncertainty.

5 Conclusions

Automating of debris removal in under-construction tunnel is a complex task due to the harsh conditions of the environment that invalidates most of the well established techniques for localization and navigation. In this paper we presented the process of converting a standard dumper into an autonomous vehicle showing the different steps taken for instrumenting the platform and for developing and setting up the system architecture.

Planning and navigation techniques have been adapted to the special characteristics of the environment and a scheme to achieve an effective localization has been proposed, based on the integration of different, sometime mutually exclusive, measurements coming from different on-board sources like odometry, IMU but also from the environment as natural (roughness of the walls), semantic (lateral galleries, dead-ends, etc) and radio-frequency features.

Preliminary experiments have shown that we are on the right direction and that the most basic of the proposed navigation and localization techniques are effective in these scenarios. In the next months we intend to complete the integration of the remaining sources and test the complete system in an under-construction tunnel.

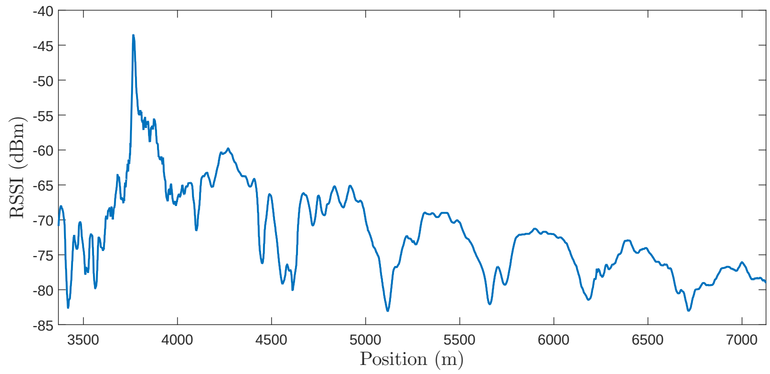


Fig. 11: Received Signal Strength Indicator (RSSI) registered over a stretch of about 3500 meters. The position is absolute. The emitter was located at about 3600 meters from the beginning of the tunnel.

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