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MAINBOT – mobile robots for inspection and maintenance in extensive industrial plants

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Abstract

MAINBOT project is developing service robots applications to autonomously execute inspection tasks in extensive industrial plants in equipment that is arranged horizontally (using ground robots) or vertically (climbing robots). MAINBOT aims at using already available robotic solutions to deploy innovative systems in order to fulfill project industrial objectives: to provide a means to help measuring several physical parameters in multiple points by autonomous robots, able to navigate and climb structures, handling sensors or special non destructive testing equipment.
MAINBOT will validate the proposed solutions in two solar plants (cylindrical-parabolic collectors and central tower), that are very demanding from mobile manipulation point of view mainly due to the extension (e.g. a thermal solar plant of 50Mw, seven hours of storage, with 400 hectares, 400.000 mirrors, 180 km of absorber tubes, 140m tower height), the variability of conditions (outdoor, day-night), safety requirements, etc.. The objective is to increase the efficiency of the installation by improving the inspection procedures and technologies. Robot capabilities are developed at different levels: (1) Simulation: realistic testing environments are created in order to validate the algorithms developed for the project using available robot, sensors and application environments. (2) Autonomous navigation: Hybrid (topological-metric) localization and planning algorithms are integrated in order to manage the huge extensions. (3) Manipulation: Robot arm movement planning and control algorithms are developed for positioning sensing equipment with accuracy and collision avoidance. (4) Interoperability: Mechanisms to integrate the heterogeneous systems taking part in the robot operation, from third party inspection equipments to the end user maintenance planning. (5) Non-Destructive Inspection: based on eddy current and thermography, detection algorithms are developed in order to provide automatic inspection abilities to the robots.

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1. Introduction

MAINBOT project is developing service robots applications to autonomously execute inspection tasks in extensive industrial plants on equipment that is arranged horizontally (using ground robots) or vertically (climbing robots). MAINBOT aims at using already available robots to deploy innovative solutions in order to fulfil project industrial objectives: to provide a means to help measuring several physical parameters in multiple points by autonomous robots able to navigate and climb structures, handling sensors or special non destructive testing equipment.

Nomenclature

PT	Parabolic Through collector
CR	Central Receiver
SCA	Solar Collector Assembly
SCE	Solar Collector Element
NDT	Non Destructive Test
HTF	Heat Transfer Fluid
FA	Functional Analysis
FMEA	Failure Modes an Effects Analysis
ROS	Robot Operating System
GPS	Global Positioning System
INU	Inertial Navigation Unit

To define the requirements of this type of industries two validation scenarios have been selected, a Parabolic Through collector technology (PT) solar plant (50Mw, seven hours of storage) and a Central Receiver technology (CR) solar plant (19.9 Mw, fifteen hours of storage) shown in Fig. 1. Both plants pose strong challenges in terms of the number of elements to be inspected, the size of the elements, the working conditions, etc. Some figures can present an idea of the magnitude of the problem in extensive plants:

- 400.000 mirrors, with a total of 1.200.000 m2 of surface in PT.
- 2.650 heliostats (10 meters high and 11 meters width) with 35 mirrors in CR.
- About 90km of absorber tubes to be inspected (180 km) in PT.
- A tower of 140 m, at 120m receiver tubes area of 11m height

a b

Fig. 1. Solar plants used for validation; (a) parabolic through, (b) tower

Based on a set of selection criteria (positive impact in plant, novelty, feasibility, risk), several operations, to be performed autonomously by the robots, are selected:

- **Ubiquitous sensing.** The reflectivity index of the plant is a parameter of paramount importance in order to decide the cleaning and maintenance activities. Measurement of reflectivity is taken by a special purpose sensor, the reflectometer. A global field reflectivity index is obtained statistically using specific measurements in chosen mirrors from the solar field. The ground robot places a reflectometer on the specific points of the SCE, touching the mirrors and recording data.

- **Leakage detection**. In PT plants, Heat Transfer Fluid (HTF) circulates at high temperature (around 390ºC) inside the absorber tubes. HTF leakages are no desirables because oil must be replaced and this operation needs to put the SCE's out of service during two or three days. Robots using thermography inspection techniques are performing this detection.
- **Surface defects detection in vertical structures**. In CR plants a receiver located at the top of a tower heats molten salts. The receiver is a polyhedral structure composed of several panels of pipes. Receiver pipes have an external coating in order to improve radiation absorption. This coating has a thickness of microns. The climbing robot moves on top of those panels performing eddy current inspection, to assess the status of the coating by measuring its thickness. Moreover, a visual camera records external surface to detect loss of coating.
- **Surface defects detection in horizontal structures**. It is estimated that 2% of the mirrors must be replaced every year, and 0,83% mirrors are permanently broken in the plant. Ground robots in the plant look for broken mirrors since early detection can contribute to improve this efficiency. In addition, the ground robot patrolling at night and using thermography inspection is used to identify any kind of loss of vacuum in absorber tubes.
- **Internal defects detection**. Detection of corrosion and internal defects in general (cracks, etc.) is required in many components in a power plant. The climbing robot will test the presence of this kind of possible defects in the collector tubes.

This paper is structured as follows, section 2 shows the design requirements and a description of the robots used in the project, section 3 explains in detail all the basic technologies developed to endow MAINBOT robots with the capabilities to autonomously perform maintenance activities, section 4 explains the different NDT approaches selected to detect degradation problems in industrial plants. Finally section 5 provides the main conclusions and future work.

2. Robot design

In MAINBOT new robotic platforms are re-designed considering all the requirements defined in the application scenarios and using previously existing platforms as a starting point. Table 1 shows a summary of the requirements considered.

Table 1. Requirements summary.

Task	Applies to	Robot Requirements	Inspection requirements
Ubiquitous sensing	Ground Robot	(1) Precise positioning to reach specific points (2) Localization (15 points in a SCE, 33 SCA) (3) Obstacle avoidance strategies	(1) On line inspection (2) Accurate sensor placement on top of a surface (3) Trajectories (reach points, Linear in Loops, Terrace)
Leakages	Ground Robot	(1) Localization (joints, sensor field of view) (2) Trajectories (reach joints, Linear in Loops, Terrace) (3) Obstacle avoidance strategies	(1) On line inspection (2) Simultaneous inspection (visual servoing)
Surface defects	Climbing Robot & Ground Robot	(1) Access to vertical areas and autonomous movement and securing at object. (2) Non contact sensor manipulation (3) Contact sensor manipulation	(1) On line inspection (2) Accurate guiding of visual camera along surface (e.g. tubes of receiver) without contact (3) On line eddy current inspection with constant contact forces
Internal defects	Climbing robot	(1) Contact based sensor manipulation (2) Localization (sensor field of view)	(1) On line inspection (2) Accurate guiding of NDT sensors along surface (e.g. tubes of receiver) with constant contact

	(3) Trajectories (continuous, according to scanning, Terrace)	forces

In addition, a Reliability, Availability, Maintainability and Safety (RAMS) methodology, applied to the robots re-design, has been followed. Based on the validation scenarios several analysis have been performed and both, hardware and software levels have been considered.

- **Functional Analysis.** The Functional Analysis (FA) is a top-down structured and systematic evaluation of both robot types. It is a qualitative method to identify and analyze all the functions related to the systems and subsystems integrated into each robot. The purpose is to assure that the robot does not cause or contribute in a significant way to personal injuries and/or material damages. This approach is combined with the design FMEA approach to obtain a list of potential Failure Modes, with their consequences and the existing / proposed mitigations.
- **Reliability and Maintainability Analysis.** The objective is to calculate or predict the reliability of a robot at different stages during their design. Once the distributions for the Reliability and the Maintainability of each component have been calculated, simulation is used to calculate the Availability (A) of the whole robot. To evaluate system availability Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) are considered. Combining Reliability Block Diagram (RBD) representation with Monte-Carlo simulation allows evaluating Availability when there are complex configurations (based on time dependant distributions).

Based on all these requirements ground robot and vertical robot have been re-designed.

2.1. Ground robot re-design

As illustrated in Fig. 2, the ground robot is built around a rigid mechanical structure adapted to the off-road navigation. The ground robot is an electrically driven, 4 wheel-drive / 4 wheel-steer mobile robot base and has a very good clearing capacity, offering a real solution for reconnaissance, monitoring and safety operations while minimizing human risks. It uses a hydropneumatic suspension capable of absorbing high and low frequency vibrations induced by the ground.

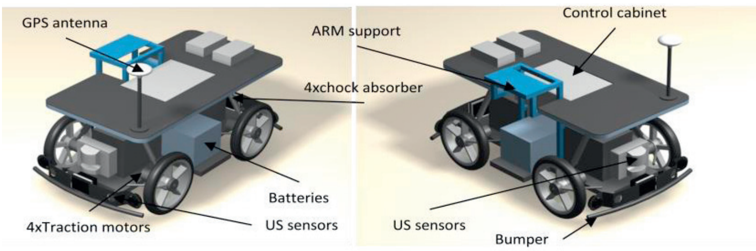

Fig. 2. Ground robot description

2.2. Climbing/vertical robot re-design

The MAINBOT approach for the is to design the climbing robot for maintenance tasks of large plants not from the scratch but using and adapting a existing robot design [1]. The physical structure of the climbing robot is shown in Fig. 3.

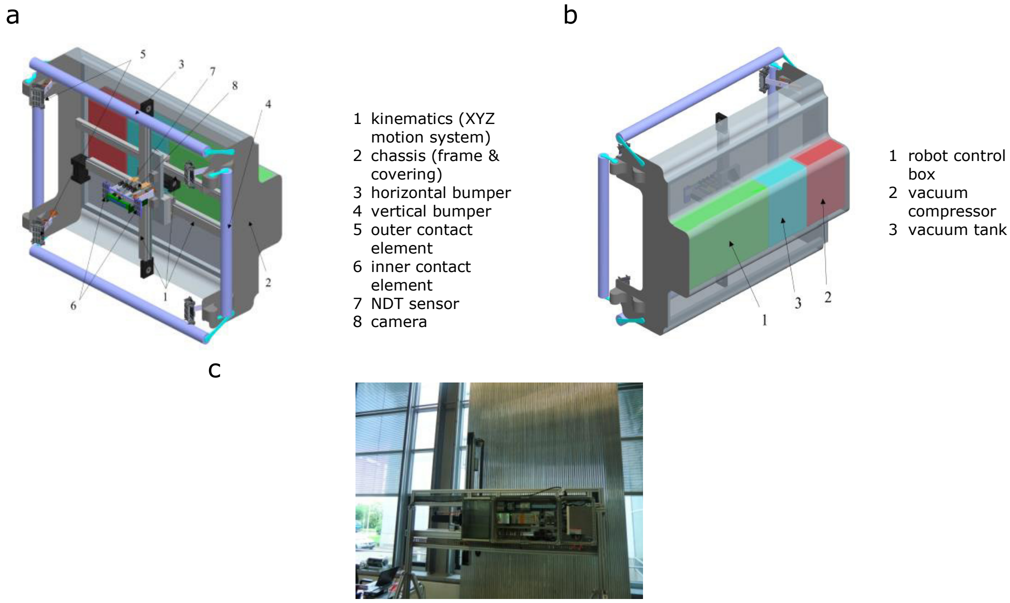

Fig. 3. Climbing robot; (a) front view, (b) back view, (c) prototype in a mockup

3. Autonomous navigation and manipulation

The aim is to endow the robots with the capability to autonomously navigate and manipulate in unstructured environments.

3.1. Simulation

3D simulation is a powerful tool for exploring what-if scenarios and for providing valuable information before developing real prototypes. Benefits of using 3D simulation in robotics come from: the ability to develop robotic applications without hardware dependency and the cost reduction.

In MAINBOT realistic testing environments have been created in order to validate the algorithms developed using available robot, sensors and application environments. A 3D simulation is used for evaluating the use and implementation of the ground mobile base and the manipulator in maintenance activities. After the analysis of state of the art simulation environments such as MORSE [2], Webots [3], UsarSim [4], finally Gazebo [5]has been selected. Using different CAD files representing the environment (the validation scenario) the ground robot provided by the robot manufacturer and the arm, a Gazebo model has been built for the complete ground robot system as shown in Fig. 4.

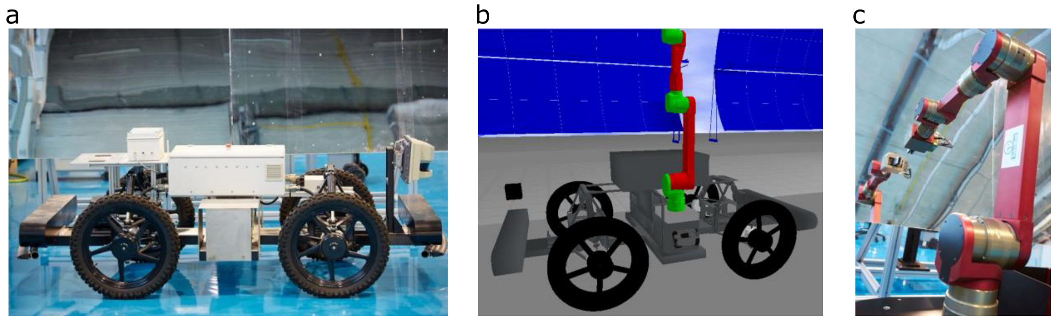

Fig. 4. Simulation environment; (a) Ground robot base, (b) Simulated ground robot, (c) Ground arm

3.2. Navigation

The navigation algorithms integrated in MAINBOT are designed to build a representation of the environment and generate robot trajectory plans considering the requirements of maintenance activities. Thus, several navigation strategies are considered, by the one hand, for ground navigation and on the other hand for vertical navigation.

In the case of ground robot, to navigate, the robot needs a representation of the environment given as a map. Navigation techniques heavily depend on the type of maps used. Most current localization systems use global, metric maps of the workspace. While convenient for small areas, global metric maps have inefficiencies of scale and in addition, are sensible to inaccuracies in both map-making and odometry performance of the robot. Because of the abovementioned reasons, it is becoming common in the field of mobile robotics to use hybrid maps that integrate different representations. Several authors [6] [7] propose combining the topological and the metric paradigm and they have shown that characteristics of both can be integrated. In MAINBOT the approach is to use a hybrid map consisting of a topological graph overlaid with local occupancy grids. As MAINBOT scenario is a completely outdoor scenario the localization problem is solved integrating a dGPS system, an RTK 2 (0.02 m accuracy) with a GPS/INS (inertial navigation system) to overcome the lack of information when GPS signal is lost.

The general localization approach in the vertical robot was adapted to the polygonal shape of the receiver scenario. Hereby the robot position relative to the tube panels is important for conducting accurate measurements with the onboard sensor equipment. The sensor localization depends on the position of the crane, the cable winches and the robot movement influenced by external facts such as wind forces and (contact) forces due to interaction with the panels. For the operation of the climbing robot at vertical structures global and local localization functions are considered:

- Global positioning at the receiver above the selected panel and at the right tower height for docking the robot to the panel and for climbing at the panel.
- Local positioning of the NDT sensors and cameras at the receiver tubes relative to the robot at the tubes generatrix and maintaining distance to the panel constant.

3.3. Manipulation

Robots working in unstructured environments have to be aware of their surroundings, avoiding collisions with any kind of obstacles. The manipulation algorithms integrated in MAINBOT are designed to build a representation of the environment using a set of sensors (laser, ultrasound, vision) and generate robot trajectory plans considering the requirements of maintenance activities. Thus, several planning strategies are considered:

- Planning arm movements with collision avoidance.
- Relative arm movements guided by sensory input.

These strategies allow providing mechanisms in order to perform inspection activities such as positioning of a inspection elements on a surface or tracking an element based on input coming from the inspection system.

3.4. Interoperability

The interoperability of the heterogeneous elements in the robotic solution is guaranteed by a general architecture on top of ROS [8] middleware that facilitates the organization, the maintainability and the efficiency of the software.

Fig. 5 shows the general overview of the robotic architecture: the robot receives as input maintenance tasks called missions either from the user interface (GUI) or an external application (End User). Afterwards, the Manager is in charge of decomposing the missions into tasks that can be performed by the Robotic Components. As explained before, the maintenance robotic system consists of several subcomponents like a mobile base, a manipulator and inspection sensors and systems, etc. During mission execution the Inspection Systems provide feedback about the status of the plant facilities.

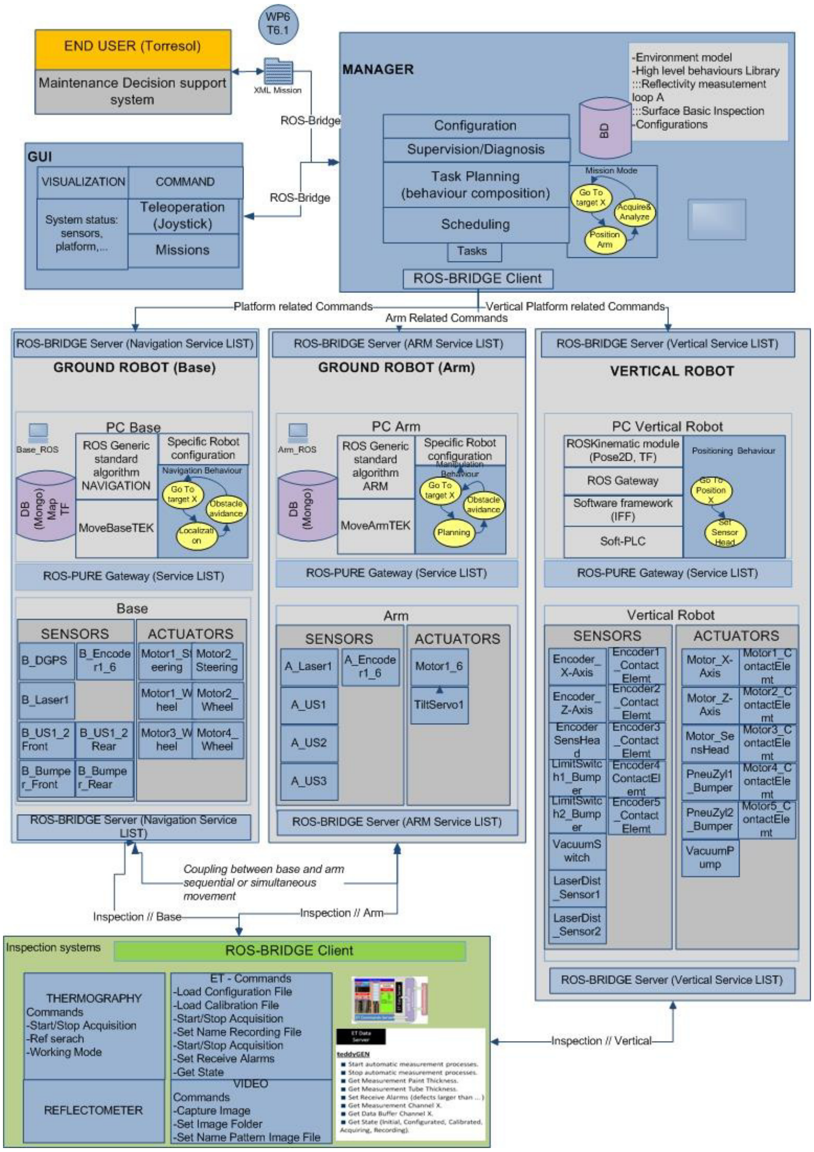

Fig. 5. System architecture

4. Non-destructive inspection techniques

Non Destructive Test (NDT) techniques are used to assess the different degradation problems to be tackled in an industrial plant: surface defects, leakages and internal defects.

4.1. Eddy current technology

Eddy current inspection is one of several NDT methods that uses “electromagnetism” as the basis for conducting examinations. Eddy current technique allows measuring coating thickness or tube thickness. Existing NDT instrumentation has been selected and adapted to MAINBOT requirements. Two types of ET sensors have been designed and manufactured: low frequency coils (to operate around 1 KHz) and high frequency coils (to operate around 1.5 MHz) shown in Fig. 6. The sensors are protected with a sapphire layer, to protect both tube paint layer and sensor surface. Raw eddy current data is processed on line, and compared with previously calibrated data.

Visual inspection is simultaneously carried out to detect external degradation in the tubes. This information is combined with eddy current data (data fusion).

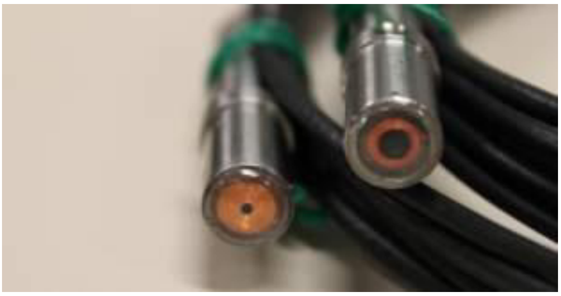

Fig. 6. Eddy current sensor coils

4.2. Thermography technology

When a tube is degraded, and there is a vacuum loss, a gradient of temperature can be detected. The algorithm performs several operations on the thermal images acquired with a thermographic camera (FLIR ThermoVision® A20) that is mounted on the ground robot manipulator in an eye-in-hand configuration. Fig. 7 shows an example of the thermal image when vacuum lost is detected. The detection algorithm works in real time coordinated with the ground robot manipulator movements. The tracking algorithm calculates the arm movements in order to hold the tube in the field of view of the thermal camera.

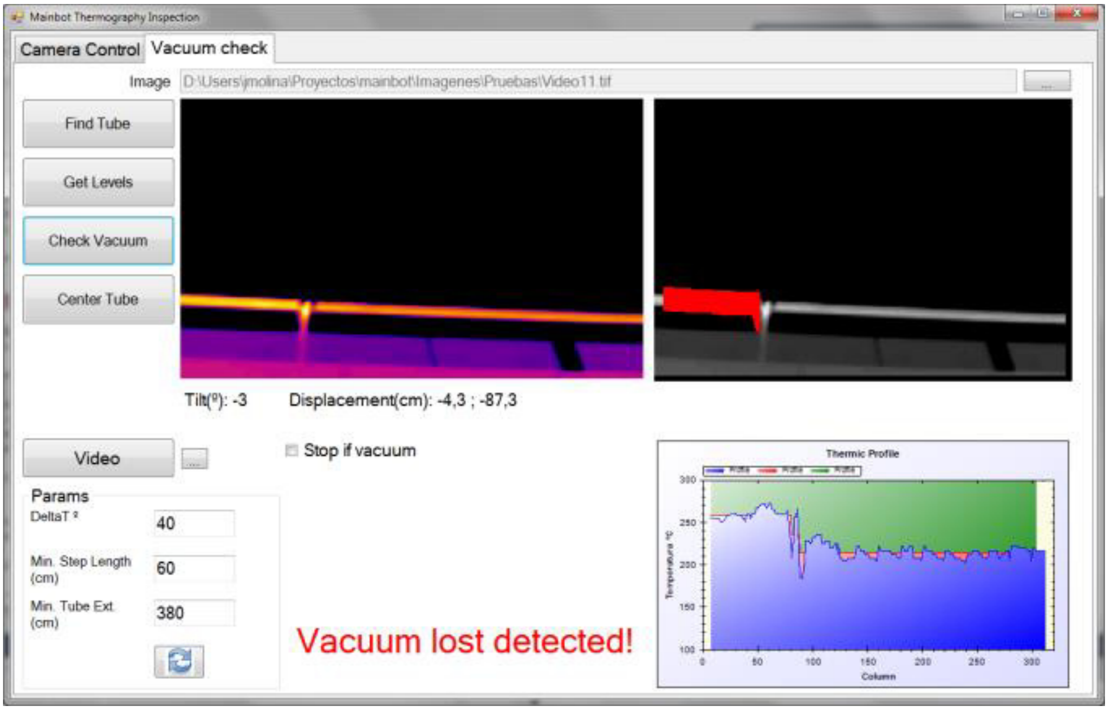

Fig. 7. Results of thermography inspection system, detecting vacuum lost

5. Conclusions

Efficient and effective maintenance is crucial for all kind of industries. In the case of capital intensive investment industries it is even more relevant and has an important impact in the operation costs during the long life cycle of their production means.

MAINBOT proposes using service robots to autonomously execute inspection tasks. A set of application scenarios that cover the general requirements of the maintenance activities in large industries have been selected.

Two kind of robotic solutions are developed in MAINBOT. Ground robot, a mobile manipulator composed of a mobile base and a 6DOF manipulator. The ground robot has to move in a large area, the solar field, and it has to reach different inspection areas in the plant and stop at pre-established points.

The vertical robot consists of a mobile base and an internal arm for inspection system positioning. The climbing robot has to move in a vertical structure, a tower.

MAINBOT is developing technologies for ground autonomous navigation and manipulation. Eddy current and thermography based algorithms have been developed and integrated in robotic platforms.

In the near future the validation of the development will be performed in two solar plants in the south of Spain.

Acknowledgements

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