Non-destructive inspection in industrial equipment using robotic mobile manipulation

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Abstract. MAINBOT project has developed service robots based applications to autonomously execute inspection tasks in extensive industrial plants in equipment that is arranged horizontally (using ground robots) or vertically (climbing robots). The industrial objective has been to provide a means to help measuring several physical parameters in multiple points by autonomous robots, able to navigate and climb structures, handling non-destructive testing sensors. MAINBOT has validated the solutions in two solar thermal 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, with 400 hectares, 400.000 mirrors, 180 km of absorber tubes, 140m height tower), the variability of conditions (outdoor, day-night), safety requirements, etc. Once the technology was validated in simulation, the system was deployed in real setups and different validation tests carried out. In this paper two of the achievements related with the ground mobile inspection system are presented: (1) Autonomous navigation localization and planning algorithms to manage navigation in huge extensions and (2) Non-Destructive Inspection operations: thermography based detection algorithms to provide automatic inspection abilities to the robots.

INTRODUCTION

MAINBOT project has developed 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 has used already available ground robot and arm and develop a new climbing robot 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.

Robots are being used in different maintenance applications: in power distribution line monitoring [1], nuclear power plants inspection [2], pipes inspection [3] or underwater pipes inspection [4]. In general, they are ad-hoc mechatronic solutions. There are also some general purpose wheeled platforms, such as [5] for offshore inspection, [6] for remote dangerous area inspection or [7] used in Fukushima. They are usually remotely controlled.

To define the requirements of this type of industries two validation scenarios were 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). 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 with receiver tubes area of 11m height at 120m above the ground

Based on the selection criteria (positive impact in plant, novelty, feasibility, risk) several operations to be performed autonomously by the robots were selected.

- **Ubiquitous sensing.** Measurement of reflectivity is done manually by operators using a special purpose sensor, the reflectometer. A global field reflectivity index is obtained statistically using specific measurements in selected mirrors of the solar field. In the project, the ground robot places a reflectometer on the points of the SCE specified by the plant Operator, 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 for several hours. Robots using thermography inspection techniques can perform 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 can be used to identify any kind of loss of vacuum in receiver 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 can test the presence of this kind of possible defects in the collector tubes.

In order to validate the results achieved, several qualitatively and quantitatively metrics were defined and used during the experimental test.

Experiments related to the abovementioned operations have been performed by the robotic platform in a thermal solar plant using parabolic-concentrating technology in the south of Spain (VALLE 1 and 2) and are described below in this paper, as well as the evaluation of navigation algorithms.

The results of the climbing robot are described in [8].

Ground Robotic platform overview

The ground platform is compound of two main elements: a wheeled robot based on the robucarTT platform and a 6 DoF robuArm robotic arm mounted on it. Both elements have been based on commercial-off-the-shelf products developed by Robosoft, one of the participants in the project. The modifications have included the modification of the battery system to increase its autonomy and the inclusion of a DGPS system to obtain a more accurate localization system.

The robucarTT platform uses a hidroneumatic damping system that absorbs high and low frequency vibrations, making it suitable for outdoor use. It has an Ackerman configuration with 4 driving electrical wheels that can be controlled independently. The robuArm mounted on the platform has 2,5kg payload and 1mm repeatability. Laser rangefinders, ultrasound sensors are used to ensure safety.

The software to control the mobile manipulator has been developed using the Robotic Operating System (ROS).

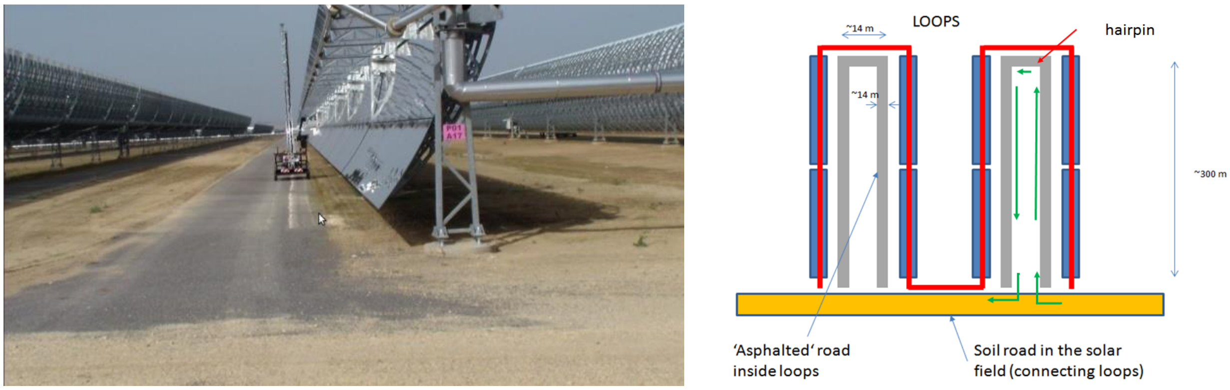
The robotic arm manipulates the two sensing devices used for non-destructive testing:

- A reflectometer
- A thermographic camera

EVALUATION OF NAVIGATION INSIDE A LOOP

In this experiment the robotic platform had to navigate autonomously inside a loop at the Valle facilities detecting any possible obstacle and maintaining a predefined distance with respect to the mirrors.

The navigation is mainly done at night, but the experiments were conducted during the day.



(a) (b)

FIGURE 1. Robot navigating inside a loop (a) and scheme of loops (b)

The platform moved at a target speed of 0.65m/s when entering in the loop and a target speed of 0.5m/s while moving straight alongside the mirrors. This lower speed was required to obtain a more accurate final positioning.

During the navigation, all available data from the platform was recorded for later analysis. The platform repeated the maneuver five times inside a loop and four different areas have been considered: the loop entrance, alongside the mirrors, the hairpin turn and the loop exit.

The length of the trajectory performed by the robot and the time required to do it was registered. Using both values, the mean speed was calculated. The efficiency in time is measured as the difference between the theoretical time needed to complete the path given a target velocity and the real time employed.

The error between the final goal pose and the one measured by the DGPS system is used to measure the accuracy.

As it can be seen in the table below for the movement inside a loop the trajectories executed and real velocity are very close to those planned.

During the experiment the platform completed the goals all times it was sent to navigate inside the loop. The table below summarises the accuracy in the goal and the time needed to reach the goal.

TABLE 1. Errors during the navigation inside a loop

Navigation area	Planned path length (m)	Performed path length (m)	Duration (s)	Target_speed (m/s)	Mean speed (m/s)	Time diff (s)
Loop entrance	22,28	22,29	31,64	0,65	0,70	-2,2
Alongside the mirrors	289,58	289,81	585,08	0,5	0,49	-4,3
Hairpin turn	23,77	24,09	33,5	0,65	0,71	-1,9
Loop exit	14,58	14,59	23,42	0,65	0,62	-1,6

EVALUATION OF NAVIGATION OUTSIDE A LOOP

Three types of tests were performed:

- Transition from one loop exit to the adjacent loop entrance. During the transition from one loop to another the robot must move through an unpaved road
- Navigation through the solar plant It includes the transition from one terrace to another, i.e. climbing steep slopes through an irregular terrain, crossing bridges as in the picture below, etc.
- Taxing from the robot park area to the solar field (to the nearest loop entrance). It includes some paved paths

The platform had to navigate autonomously five times in each area, trying to reach a target position, meanwhile all data available was recorded for offline analysis of the error in X, Y position, the Yaw error and the time difference with the theoretical value.

(a) (b)

FIGURE 2. Robot navigating form one loop to another (a) and navigating in the plant (b)

The robot completed the goal successfully all times.

The table below summarises the accuracy on average in the goal and the time needed to reach the goal in the case of taxing. The errors are mainly due to the position algorithm that tries to optimize the time to converge.

TABLE 2. Errors during the navigation taxing from car park to the loop

Goal error in X (m)	Goal error in Y (m)	Goal error in Yaw (rad)	Time diff (s)
0,1398	0,486	0,1788	-10,377

VACUUM LOSS DETECTION

HTF circulates inside the absorber tube, which is compound by an inner metallic pipe and an outer glass cover. Between these two elements there is vacuum. Broken glass and vacuum loss lead to a loss of heat and as a consequence to a reduction of plant efficiency. MAINBOT proposes the ground robot patrolling at night and using thermography inspection to identify this kind of problems.

Two different experiments have been performed to test vacuum loss algorithms, based on the information provided by the thermography camera.

In the first one, they were analyzed thermal images corresponding to 13 km of tubes from Valle 1 and Valle2. The images were acquired at night (from 23:00 pm to 4:30 am) from a car traveling at 20 Km/h.

In the second one, the analyzed data was acquired from the camera mounted on the robot arm at the target speed. It was selected a loop in which vacuum loss presence was known: six vacuum losses, three of them in consecutive tubes. The arm was positioned so that the tube remained horizontally in the center of the thermal image. The robot travelled 3 times alongside the loop at 0.5 m/s (1.8 km/h) speed. The operation was done at daylight and at night.

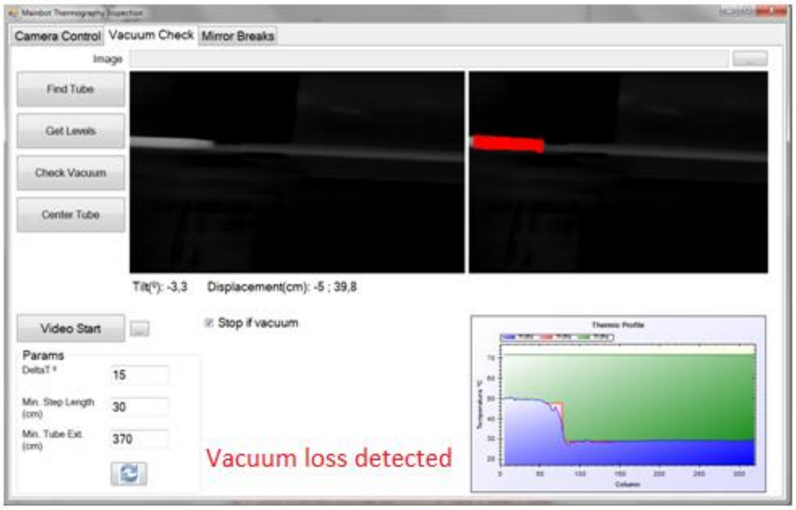


FIGURE 3. Application developed for vacuum loss detection

The previous picture, shows the application developed to automatically identify the vacuum loss, the thermal image, the area with the problem and the gradient of temperature.

The algorithm detected all of the vacuum losses present without giving false positives or false negatives, obtaining a detection ratio of 100%.

To the success of the operation, the thermography camera had to be maintained at a proper orientation and distance with respect the object to be inspected, in order to maintain the target object in the field of view of the camera. Several tests were successfully carried out as described in [9].

BROKEN MIRRORS DETECTION

As explained before, it is estimated that 2% of the mirrors must be replaced every year, and 0,83% mirrors are broken in the plant at any time.

The heuristic used to detect broken mirrors is based on the analysis of thermal images, using the background as temperature reference.

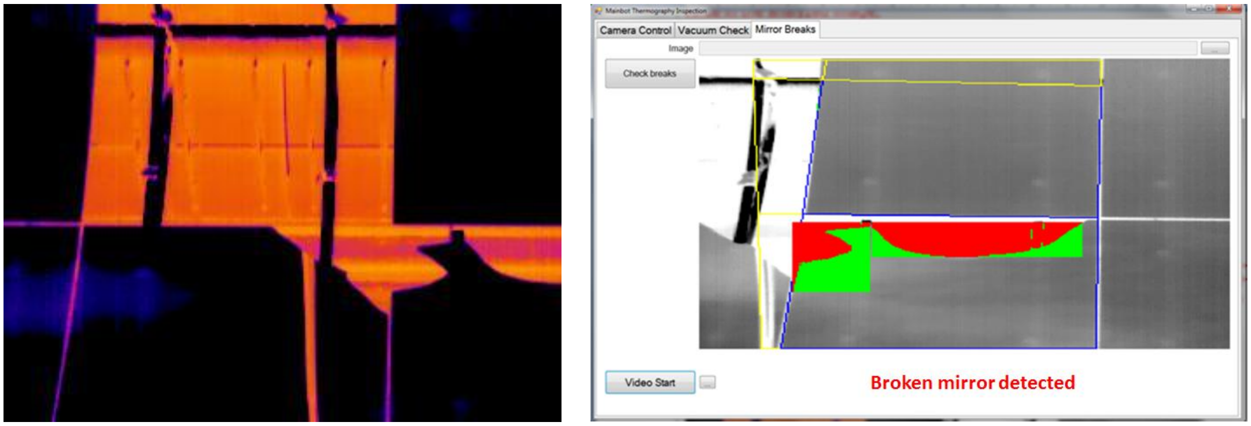
The developed algorithm is based on finding the facets present in a thermogram and analyzing them (other strategies, such as tracking the border of each mirror were discarded due to the huge amount of time required to inspect all the mirrors in the plant.). The analysis includes:

- To convert the thermal information present in the thermogram into gray scale image.
- A Hough lines algorithm is applied to find each of the facets present.
- With each facet a dynamic threshold is applied.
- Finally the resulting blobs are filtered based on area dimension, shape and circularity criteria.

Due to the reflective feature of mirrors, the thermal camera receives the reflection from the mirror in the direction of the camera and the radiation reflected by the neighbor elements (facets, tubes and other structural components). These reflections are perceived as an element with a higher temperature.

Taking this into account, the algorithms has to follow different approaches depending on the position of the facets: facets on top of the SCE have the sky as background meanwhile facets on the lower part of the SCE have not.

In the first case (background sky) both the detection of each facet and the search for breakages is performed with high detection rate because of the great contrast between the surface of the mirror and the rest of the scene. Next picture shows an example of the image obtained from the thermal camera and the result provided by the application. In this case, the breakages in the mirror are seen as part of the rest of the scene, and a geometrical discontinuity in the facets provides the information to detect the breakage.



(a) (b)

FIGURE 4. Thermal image of a broken facet (a) and application for automatic detection (b)

In order to test the algorithm, two different thermal sequences of a loop were acquired (upper part and lower part of the SCEs). It is noteworthy that breakages are more frequent in the lower part of the SCEs.

The results are quite different depending on the mirror position. In upper facets breaks with an area greater than $90cm^2$ from a distance of about 12 meters were found. In the case of lower facets in the SCE, the algorithm is able to detect breakages of the same area but with an horizontal length longer than 8cm and a circularity greater than 0,2, to avoid typical structural reflections present in the mirrors, assuming that breakages present a proportional aspect (based on experience).

LEAKAGES DETECTION

Heat Transfer Fluid (HTF) circulates at high temperature (around 390ºC) inside the absorber tubes. HTF leakages are no desirable because the repairing implies putting the SCE out of service during a long period of time. Robots using thermography inspection techniques are proposed to detect this problem.

Leakages can be detected with infrared cameras sensitive in the wavelength where the gas has absorption peaks. With the appropriate infrared camera, leakages can be perceived as steam. Taking this into account it has been implemented an algorithm based on optical flow which is able to detect the presence of steam in a scene.

The validation of this algorithm is only possible using a camera in the range of the HTF emission. This type of cameras are very expensive and were not available. As a consequence, it was decided to test the algorithm with a different gas. An experiment was done using a vaporizer. The camera focused the output of steam of the vaporizer. The objective was to detect the movement of steam particles.

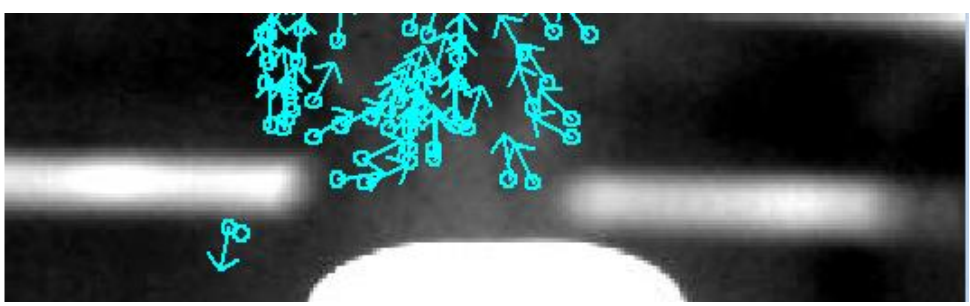


FIGURE 5. Optical flow used to detect steam

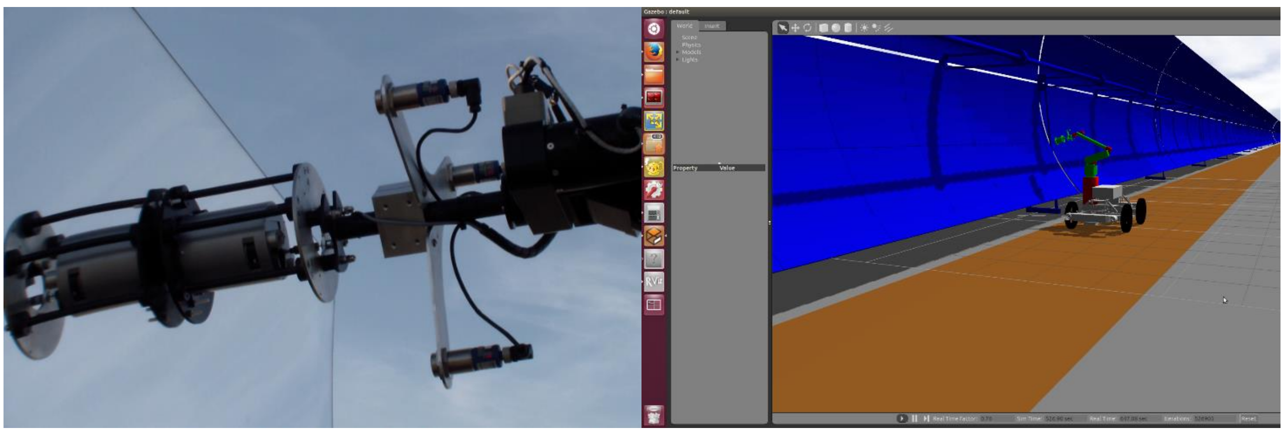
Once the algorithm was verified with the vaporizer and knowing that without mid-wave infrared sensitive equipment it was not possible to validate with HTF gas, it was found a non visible innocuous gas to emulate the ral situation more realistically. The chosen gas was acetic acid that is visible with the available long-wave thermal camera at ambient temperature.

In all the test, performed in laboratory conditions, the presence of steam was successfully detected in all tests.

REFLECTIVITY MONITORING

The reflectivity index of the plant is a parameter of paramount importance in order to establish an optimal cleaning policy. Measurement of reflectivity is currently done manually by operators using a reflectometer. The MAINBOT has tested the ground robot placing the same reflectometer on the points of the SCE that TORRESOL uses as reference and recording the acquired values.

The objective of this experiment was to doublecheck the accurate and safe placement of the reflectometer on the surface of the mirror. To achieve this objective, the platform navigates up to the mirror to be inspected, the reflectometer toolholder is positioned parallel to the mirror and the approach manoeuvre is performed until the sensor touches the mirror. The signals provided by 3 ultrasound sensors in the toolholder are used for trajectory control.



(a) (b)

FIGURE 6. Robot placing the reflectometer on the mirror (a) and simulation environment (b)

During the experiments the sensor was successfully positioned on the mirror, without any kind of damage, neither on the mirrors nor on the reflectometer. The time required for reflectivity measurement was about 7min for each SCE in the experimental conditions.

As all loops have the same layout, it was possible to design an optimized navigation algorithm to reach the target measurement positions. The procedure is as follows:

- To setup the input point of the loop. The robot is placed at that target point and the position and orientation provided by the DGPS is registered.
- Calculation of the five inspection positions of the ground robot in a SCE.
- To establish the configuration of the manipulator to perform the measurement on the mirror.

Once the target measurement points are defined the reflectivity measurements operation is autonomously performed: the Robot moves to the initial position in loop, then the robot navigates to the first measurement point and places the tool over the mirror. The procedure is repeated along the rest of SCEs. Once the measurements are performed, the robot exits the loop to continue with the next one.

CONCLUSIONS

By means of the experiments, all selected operations have been validated and the feasibility of automated inspection operations has been demonstrated.

Thermography technology is a very useful tool in extensive plants inspection due to three main reasons.

- It is a non-contact technique
- It allows affording many different kind of problems: vacuum loss, surface defects and leakages.
- It provides rich data that can be processed very quickly.

In the case of **vacuum loss** high detection ratio (100%) has been achieved and the detection algorithm has been automated so that it has been integrated in the robot control.

Broken mirrors detection has been also solved with thermal analysis, however during final validation at Valle results were different depending on the position of the facets. Better performance was achieved in the upper part of the SCEs.

Leakages detection has been validated in laboratory conditions (it was not possible to validate it in a solar plant due to the wavelength of HTF and the camera available for the experiments) implementing optical flow algorithms that can detect vapor particles movement in the images.

Reflectivity measurement has been performed using the manual reflectometer (the most widely used in this kind of facilities). The key problem (positioning of the sensor on top of a fragile surface, i.e. the mirror) has been validated. A real implementation will demand a different approach to include the reading of the sensor values to close the positioning loop and a procedure for periodic re-calibration of the sensor.

From the **navigation** point of view, the combination of the implemented planners (SBPL, line follower, and hairpin) has provided efficient trajectories. On the other hand the robot was able to successfully deal with the rough terrain encountered at the end user facilities (slopes and irregular unpaved paths in some areas).

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