PROJECT FINAL REPORT

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Project acronym: MAINBOT

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Content

1 Technical report

1.1 Final publishable summary report

1.1.1 Executive summary

MAINBOT project has developed service robots to autonomously execute inspection tasks in extensive industrial plants on equipment that is arranged horizontally (using ground robots) or vertically (climbing robots). MAINBOT has taken as starting point already available robotic platforms and technologies to deploy innovative solutions in order to fulfil the industrial objective of the project: ***to increase the efficiency of industrial installations by improving the inspection procedures and technologies to assess their status by means of autonomous robots able to navigate and climb structures, handling sensors and non-destructive testing equipment***.

The type of inspection tasks that are performed are very diverse and depends on the type of industry, the nature of assets and maintenance practices of end-users. MAINBOT has selected a set of activities that are representative of those tasks at a great extent:

- Ubiquitous sensing

  It includes those activities that demand an operator to move to specific points in the plant, take measures and analyse them.

- Internal and external assets monitoring

  It includes those inspection tasks that use non-destructive techniques to assess the status of an asset, such as pipes or tanks, which can present external or internal faults (such as corrosion or cracks).

- Leakages detection

  Fluids or gas flowing by pipes or confined in tanks can accidentally flow outside. Its early detection can reduce the risk of accidents and increase plant efficiency

MAINBOT has developed two different categories of autonomous robots, one able to navigate and inspect elements deployed in horizontal environments and a second robot able to climb and inspect elements deployed vertically.

Both concepts have been successfully validated in two thermal solar plants that are very demanding from the mobile manipulation point of view due the variability of conditions and working field dimensions. Moreover they offer realistic horizontal and vertical scenarios.

The achieved results lead to a TRL6 for the climbing robot inspection system and TRL7 for the ground robot inspection system.

The consortium has identified the business models that will make possible to market the technology developed and the knowledge acquired in the short-medium term.

1.1.2 Project context and objectives

Efficient and effective maintenance is crucial for all kind of industries. In the case of capital intensive investment industries such as petrochemicals, steel industry or power generation plants it is even more relevant and has an important impact in the operation costs during the long life cycle of their production means.

Besides the traditional maintenance problems of any industrial installation, this kind of facilities presents other additional challenging characteristics:

- **Huge number of elements to inspect**. Pipes, valves, switches, pumps, vessels, motors, vibrating machinery, chillers, ovens, etc.

- **Multiple inspection technologies to be used:** visual inspection (leaks, corrosion, paint condition, insulation condition, misalignments,...), thickness and surface status assessment (e.g. corrosion, painting or coating status) using Ultrasonic, eddy current techniques, vibration measurement, radiography, thermography, noise analysis, gas sensors, etc.

- **Extensive production facilities**. This kind of plants spreads out for thousands of square meters, conducting pipes account for several tenths of kilometres and it is not infrequent to find high chimneys or vertical structures.

- **Risky working conditions** for maintenance personnel due to the presence of hazardous materials (in case of inhalation or contact), high voltage elements and wires, need to work at height, etc.

Currently, the most common way to maintain equipment working properly is the implementation of a preventive maintenance plan.

- **Periodic maintenance:** it may be done at fix calendar intervals, after a specified number of operating cycles or hours. These intervals are established based on manufacturers' recommendations, and utility and industry operating experience.
- **Condition based maintenance:** it assumes that equipment failure modes will follow known degradation models and that, using measurement and inspection techniques and visual inspection it is possible to predict its future behaviour or remaining life.

Non-destructive inspection techniques are key factors to establish appropriate preventive maintenance policies and actions. The status assessment is addressed according to different criteria:

- By **intensive human force employment** in inspection tasks. Due to the multiple technologies involved and the skills need to operate the measuring equipment, the above mentioned huge dimension of plants and the number of inspection points, Maintenance and Inspection services require employing a great amount of operators travelling across the plant.

- **Optimizing the frequency of inspection** based on previous experience.

The intervals are usually set up by the manufacturers during the design phase, generally based on their intuition or on subjective estimations for the life expectancy of the different components. Due to the huge number of control points in the extensive production facilities it is necessary to optimize the maintenance/inspection frequencies looking for the balance between the failure probability and the consequences of the failure.

- **Deploying a huge number of sensors** (high cost) that allow continuous monitoring of some parameters. Those sensors have to be powered to operate (by wiring them or using batteries that have to be replaced periodically) and different communication mechanisms can be used: logging the information and downloading periodically, wiring the sensors, deploying Wireless Sensor Networks (WSN) or incorporating other wireless communication means. In a large and complex plant, any stationary network of sensors will not provide a precise and effective detection and, in particular, localization of weak points such as hot or cold spots or leaks might eventually become unfeasible.

- Employing uncomfortable and sometimes expensive **Individual Protection Equipment** (gloves, safety helmets, gloves, suits, boots, masks, harnesses) and other transport and access means (vehicles, cranes, etc.).

MAINBOT proposes using service robots **to autonomously execute inspection tasks in extensive industrial plants** in order to measure in-field parameters and detect degradation problems (faulty elements, corrosion and leakages, etc.) in equipment that is arranged **horizontally (using ground robots) or vertically (climbing robots).**

MAINBOT has validated the proposed solutions in two concentrating solar plants (using cylindrical trough collectors and central tower technologies) that are very demanding from the mobile manipulation point of view due the variability of conditions (outdoor, day-night), safety requirements and the dimensions of the plants:

Figure 1: Scenarios for climbing (GEMASOLAR) and for ground robot (VALLE)

- Concentrating parabolic trough collectors plant (Valle 1 and Valle 2)
  - Surface of the solar field: 400 hectares
  - More than 400.000 mirrors, i.e. 1.000.000 m2 of reflective area (mirror surface)
  - 180 km of absorber tubes

- Central tower technology plant (GEMASOLAR)
    - 140 m high central tower

The final industrial objectives of the project are:

- ***To increase the efficiency of industrial installations***
- ***To* reduce the operation and maintenance costs**
- ***To improve the safety and working conditions of workers***

And to achieve these objectives MAINBOT proposes ***improving the inspection procedures and technologies by means of autonomous robots able to navigate and climb*** structures, handling and managing sensors and non-destructive testing equipment.

These generic objectives have been instantiated in concrete objectives:

- **Ubiquitous inspection**: 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.
- **Leakage detection**: To develop a surveillance robotic system able to detect leakages of fluids and gases.
- **Surface monitoring**: Robotized non-destructive testing of surface deterioration of equipment in extensive plants and detection of broken elements.
- **Internal deterioration of equipment**: Robotized non-destructive testing of internal deterioration in pipes and walls of tanks, chimneys etc., from outside the element to be inspected.

The proposed robotic solution implies developing:

- **Ground robots** able to navigate in large industrial plants handling sensors and non-destructive equipment for inspection, overcoming obstacles and terrain conditions.
- **Robots able to climb** vertical (or almost) industrial equipment handling sensors for inspection.

To answer to these industrial objectives, MAINBOT has addressed the following **scientific and technological objectives**:

- **Autonomous ground navigation**: Robots must be able to **autonomously** navigate in unstructured environments in a **safe** way. To achieve such a degree of autonomy it has been necessary to address some challenging issues:

    - **Smart combination of topological and metric maps**. The large dimension areas the robot has to move in, introduces an additional complexity to the problem. Managing metric maps for such huge areas is not computationally affordable; however topological reasoning is not accurate enough for the requirements of maintenance applications.

Therefore, MAINBOT has developed a smart combination of both approaches.

- **Local navigation strategies adapted to inspection and maintenance activities**. In a traditional navigational problem, the robot controller has to plan the path to be followed based on the objective of achieving a target position in a map. However in the maintenance scenario the task itself (inspection) has to be used to close the navigational control loop. For instance, when inspecting a pipe using an ultrasonic sensor, inspecting the surface of a reflecting mirror, or any other inspection application, to obtain good quality sensor readings it is necessary the robot moved following specific patterns (angle, distance, velocity, etc.).

- **Autonomous climbing robots**: Climbing robots have to face the following challenging requisites to navigate in vertical structures:
  - Robots have to reach the entire surface of the vertical structures.
  - Self-planning of paths depending of simple geometrically description of the structure and information from embedded sensors.

- **Mobile manipulation** for inspection activities in order to manipulate non-destructive test equipment and sensors. The challenge is twofold:
  - Real time coordination of manipulator´s end-effector and mobile platform based on sensor information and inspection task strategy.
  - Safe manipulation of inspection devices and actuators that require physical contact with the inspected part or infrastructure.

- **Sensor fusion**: The robot must be equipped with highly reliable sensors to perceive its surroundings, not only for navigation but for inspection and manipulation. The use of robots for maintenance allows using multiple sensing technologies at the same time. To exploit the information provided by each of these technologies in a more efficient way the concept of sensor fusion has been introduced to allow considering the working conditions and environmental parameters (lighting conditions, velocity, etc.).

- A **high level task planner** is needed in order to plan robot actions for autonomous inspection missions. This task planner has to resolve specified tasks (defined by maintenance operators through Human Robot interface) and plan the resulting motions and sub-tasks for the robot. The plan generated has to include a sequence of actions (e.g. movement, picking up items, manipulating items) with assigned resources (e.g. sensors, gripper). A hierarchical planning approach has been implemented. High level tasks are decomposed in a sequence of subtasks that are managed by lower level planners (manipulator, mobile base, inspection system) to produce primitive actions (i.e. non decomposable).

1.1.3 Main S&T results/foregrounds

1.1.3.1 The methodology

MAINBOT has followed this approach to reach the scientific and industrial objectives:

- Analysis of maintenance and inspection needs in extensive industrial plants.
- Selection of inspection operations that are performed in TORRESOL plants according to different criteria
- Design of requested modifications in existing robotic platforms to answer the requirements previously identified
- Development and adaptation of inspection technologies in order to be integrated in autonomous robots
- Validation in simulation
- Integration of both robotic platforms and non-destructive technologies
- Validation using a mock-up
- Validation in real and realistic environments

In the following chapters the achieved outcomes are presented.

1.1.3.2 The industrial scenarios

As explained before, two thermal solar plants have been used to develop and validate the concept proposed by MAINBOT.

These two plants offer relevant scenarios for inspection needs in extensive industrial plants and challenging environments for ground and climbing robots.

1.1.3.2.1 Ground robot based inspection scenario. VALLE 1 and 2

These twin plants produce energy based on the solar radiation collected using cylindrical-parabolic collectors. Through these collectors a heat transfer fluid (HTF) circulates and absorbs the solar energy that is used later, to store it or to generate steam that finally is converted into electricity.

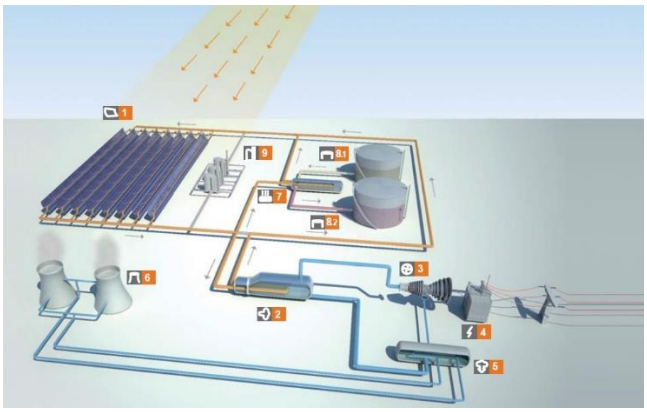


Figure 2: Valle 1 and 2 energy production and storage concept

Figure 3: Both solar fields

The main characteristics of both plants are:

- Rated electrical power per plant: 2x50 MW.
- Solar field: 2x510,000 m^2 of SENERtrough® cylindrical-parabolic collectors.
- Heat storage system: each plant has a heat storage system (base on melted salt) with seven hours' capacity.
- Surface of the solar field: 400 hectares
- More than 400.000 mirrors, i.e. 1.000.000 m2 of reflective area (mirror surface)
- 180 km of absorber tubes

Figure 4: SCAs and SCEs inside a loop

The solar field is composed loops of 4 groups of collectors called SCAs (solar collector assembly) of 150 m in length each one. Each SCA is divided in 12 smaller groups (solar collector elements: SCE). Every SCE is formed by 28 mirrors, 4 rows of 7 mirrors each. As a result each loop consist of 1.344 mirrors.

1.1.3.2.2 Climbing robot based inspection scenario. GEMASOLAR

The solar field, composed of 2,650 heliostats, reflects and concentrates sun radiation on a receptor located on the upper part of a 140 m tower. Liquid salt at 290ºC is pumped from a cold storage tank through the receiver, where it is heated to 565ºC and then stored into the hot tank. Later on this energy is converted into electricity.

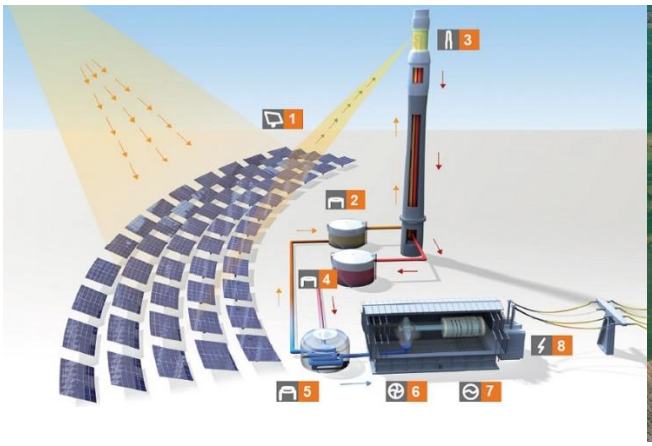


Figure 5: GEMASOLAR energy production and storage concept

Figure 6: GEMASOLAR plant

1.1.3.3 The inspection operations. Use cases

After the analysis of both solar plants a selection criteria was established in order to define the use cases. The key aspects taken into account were:

- Positive impact in plant performance
  - Improvement of plant efficiency, through better inspection practices
  - Minimal modifications in current practices
  - Compatibility with manual operations (it is easy to shift from robotized to manual operations)
  - Improvement of working conditions
  - Overall cost reduction

- Innovation: was the operation already done by robots? Did it mean an innovation in the field of robotics? Did it mean an innovation in the inspection process?
- Could the operation be applied in other industries?
- Was the solution proposed suitable to be used in other inspections/operations?
- Feasibility in terms of time needed for technological development
- Frequency of operations.
- Time employed in the inspection task.

According to these criteria the following inspection tasks have been identified:

<u>Operation 1: Mirror reflectivity measurement</u>

Mirrors are the key elements in the solar field of a Concentrated Solar Power plant. The maintenance activities include cleaning the mirrors periodically and the replacement of those broken ones.

Reflective capability of mirrors is one of the characteristics in plant design. It depends on the quality of the glass and the substrate that conform the mirror, and changes along the time due to the different factors, in particular due to dirtiness.

One of the important activities in the plant is to maintain a high level of reflectivity index. Measurements of reflectivity are done manually by means of a reflectometer. The end-user defines the number of points the reflectivity has to be measured and the frequency this operation has to be done.

An operator measuring the reflectivity of the mirror using a reflectometer. This device has to be in contact with the mirror to obtain valid values.

Figure 7: Reflectivity measurement

Robotic operation description:

- *The ground robot has to reach different SCEs in the plant.*
- *In each SCE, the ground robot stops at pre-established points.*
- *The arm is equipped with the reflectometer in its hand.*
- *The arm places the reflectometer carefuly on specific points of the SCE, in touch with the mirror (as shown in the picture above).*
- *The read values are stored in the internal memory of the reflectometer*
- *The process is repeated for each SCE established in the inspection plan defined by TORRESOL*
- *Once the task is finished the values are uploaded by the maintenance personnel for later analysis and decision taking.*

Operation 2: Heat Transfer Fluid Leakage detection

Heat Transfer Fluid (HTF) circulates at high temperature (around 390ºC) inside the absorber tubes. This temperature is achieved by concentrating the solar irradiation in the focus of the parabola. The HTF is used to heat the molten salts that are stored in big tanks. Afterwards the hot molten salts are used to generate steam in the Steam Generation system (SGS).

Swivel joints are the points where the collector tube connects with the infrastructure of pipes that are deployed all over the plant. They are critical points where leakages may happen.

Robotic operation description:

- *The ground robot patrols the solar field.*
- *When inside a loop, a vision system (thermography) takes pictures of the joint balls, meanwhile the robot moves.*
- *When a leakage is detected, a warning message is sent to the control centre with the coordinates of the problem.*

Operation 3: Surface coating degradation, corrosion and internal cracks

As explained before, GEMASOLAR plant is based on "central-tower technology". Here, heliostats (flat mirrors) reflect solar radiation onto a receiver located at the top of a tower through which molten salts flow. The salts are pumped from a 'cold tank' to a receiver located at the top of a tower where they are heated to 565ºC. The hot molten salts go down to be storage in the "hot tank", where they are pumped to the steam generation system (SGS) to produce condensed water to move the turbine.

The red circle indicates the zone of the Tower where the receiver tubes are located. These tubes have a length of around 11 meters and are placed around the tube.

Figure 8: GEMASOLAR central TOWER and inspection zone

Absorber tubes have an external coating in order to improve radiation absorption. The objective of this operation is the assessment of this coating thickness that is in the order of microns. In this range, eddy current inspection has been used.

Detection of corrosion and internal defects (cracks, etc.) is required in many components of a power plant. Depending on the material and other inspection requirements, two NDT techniques can be used:

- Eddy current: It can be applied in conductive but non-ferromagnetic materials (such as stainless steel, etc.). Maximum thickness will go from 3 mm to 6 mm depending on the material and the sensor to be proposed. The technique is used to identify corrosion (thickness reduction, presence of oxide deposits, etc.), pitting, cracks, etc.

- Ultrasound: UT techniques can be applied in many types of materials used in tubes, pipes, tank walls, etc. For thin tubes high frequencies (15 MHz) are needed. Corrosion measurements and thickness measurement in general are carried out with 0° probes. Perpendicularity of the UT beam incidence in this case is highly required. For crack detection, angular probes are recommended.

Robotic operation description:

- *The climbing robot goes to the receiver area and it is clamped to a panel of tubes. The robot manipulates the Eddy Current probes that have to be in contact with the tubes and a vision camera.*
- *The climbing robot moves along the tube acquiring and recording Eddy Current data and 2D images. Both information is correlated.*
- *The robot moves to the next panel area until the inspection is completed.*

Sensor positioning is very critical, because lift-off effect (produced by changes in sensor-tube distance) could jeopardize an accurate coating measurement.

On the other hand, a misplacement can damage the surface to be inspected or the sensors themselves.

Operation 4: Broken mirrors

As it has already been explained, mirrors are key elements in solar plants. In the case of VALLE 1&2 there are more around 400.000 mirrors with a total of 1.100.000 m^2 of reflective surface.

It is estimated that 2% of the mirrors must be replaced every year, and 0,83% mirrors are permanently broken in the plant. As it has a great impact on the plant efficiency, early detection of broken mirrors can contribute to improve this efficiency.

Robotic operation description:

- *The ground robot patrols the solar field.*
- *When inside a loop, a thermography system takes images of all CSAs.*
- *Each time a broken mirror is detected, the image and its coordinates (SCA/SCE) are registered.*

Operation 5: Loss of vacuum in collector pipes

The Heat Transfer Fluid (HTF) circulates inside the absorber tube. The tube is compound by an inner stainless steel pipe (the HTF circulates inside it) and an outer glass cover. Between these two elements there is vacuum. Vacuum loss or broken glass lead to a loss of heat and as a consequence reduction on plant efficiency. This is particularly important in windy conditions.

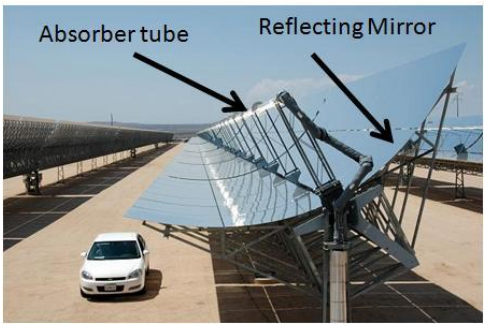


Figure 9 Absorber tube and Solar Collector Assembly.

Each plant, VALLE 1&2, consist of 156 loops, each of them 576 m long, i.e. there are about 90km of absorber tubes to be inspected per plant (180 km in total).

Robotic operation description:

- *The ground robot patrols the solar field.*
- *When inside a loop, a thermography system takes images of all absorber tubes.*
- *Each time a vacuum loss is detected, the image and its coordinates (SCA/SCE) are registered.*

1.1.3.4 The robotic solutions

Based on these use cases the two robotic prototypes have been re-designed, manufactured and the control algorithms developed.

In the redesign process it has been applied the RAMS methodology, which allows identifying in advance all the requirements of the mobile maintenance robots in terms Reliability, Availability, Maintainability and Safety (RAMS).

The method started by defining the functionalities that each robot had to perform when working in the validation scenarios. Then Functional Analysis (FA) was used for the structured and systematic evaluation of both robot components and finally a list of proposed mitigation actions that would guarantee adequate Safety levels was proposed.

1.1.3.4.1 The ground robot

The ground robot is a prototype that combines two robotic platforms: a wheeled mobile platform based on the robucarTT system and a 6 DoF manipulator based on the robuArm arm. Both platforms are commercialized by ROBOSOFT as standard solutions.

The robuCAR TT is a mobile platform composed of 4 independent driving wheels and 2 independent steering. The robuARM S6 is a 6 degree of freedom arm designed to be embedded in a mobile platform. In fact both platforms are usually commercialized together as it is shown in the picture.

Figure 10: the robuCAR TT and robuARM basic modules used as starting point

Based on the scenario analysis some new features were added to the original design and a new prototype was available as it is shown in the next figure.

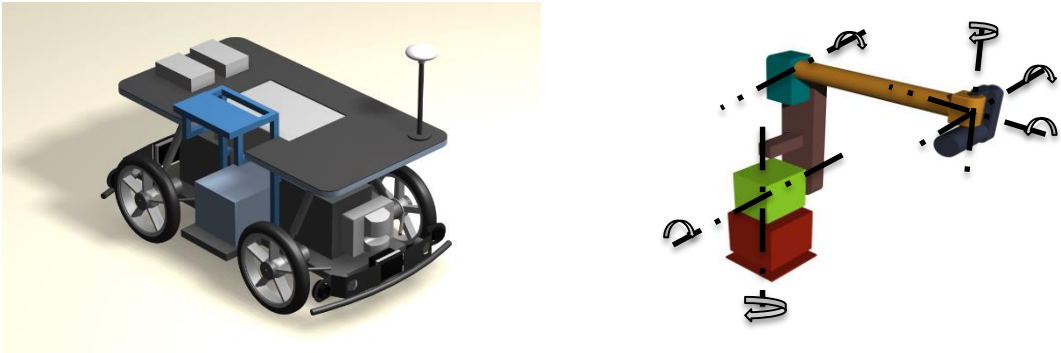


Figure 11: MAINBOT Ground robot basic units design

The robot navigates autonomously in the parabolic trough collector solar plant, performing different kind of measurements to assess the status of the mirrors and possible leakages in tubes.

Based on the design and the scenario definition a ***simulation environment*** was created and used for validation of the control strategy and operation strategy.

Using as a starting point a CAD file provided by the robot manufacturer a URDF file was created and the Gazebo model generated.

Due to the fact that the robucarTT platform has an Ackerman configuration, a special controller was developed, including a PID control loop.

Each sensor embedded in the platform has its own gazebo plug-in that publishes the data acquired. In the case of ultrasound sensors, a new plug-in has been developed because the current plug-in publishes the distance between obstacles and sensors; however the ultrasound sensors in the platform only notify if an obstacle has been detected or not but not the distance.

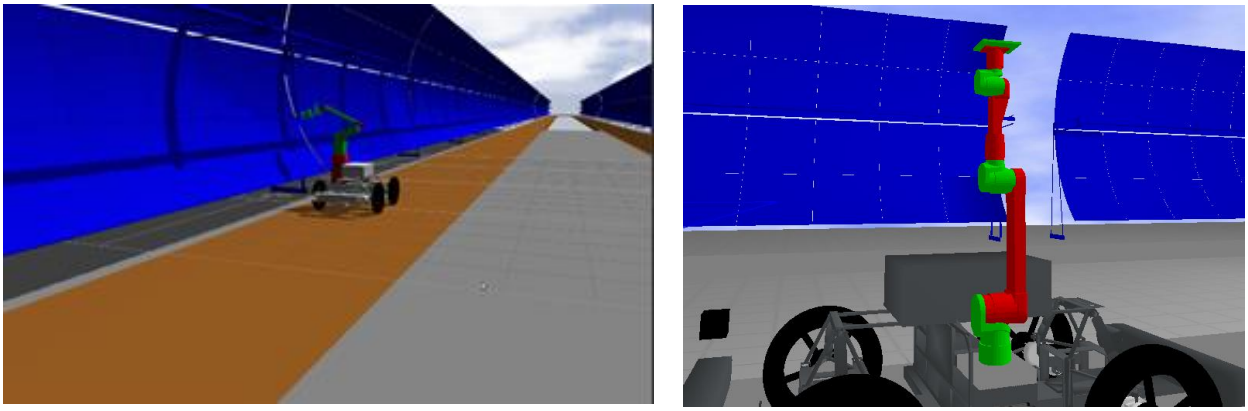


Figure 12: Simulation of the environment and the ground robot platform

Most current localization systems use global, metric maps of the workspace. While convenient for small areas, global metric maps have inefficiencies of scale, i.e. planning in a large metric map has a high computational cost. In addition, metric maps are sensible to inaccuracies in both map-making and odometry features of the robot, in large environments the drift in the odometry makes the global consistency of the map difficult to maintain.

Because of the abovementioned reasons, it is becoming common in the field of mobile robotics to use *hybrid maps* that integrate different representations. In MAINBOT the approach has been to create a hybrid map consisting of a topological graph overlaid with local occupancy grids. The environment is described by a global topological map, which permits moving in the whole environment, and local metric maps which can be used for local navigation purposes.

Since the workspace is a large area, the overall plan is created in a topological graph and the local metric information is used for achieving precise localization (needed for some operations) and collision avoidance.

Hybrid navigation aims at finding a path from point A to point B in the map, and then following it while avoiding unmapped obstacles. Figure 13 represents the elements that are part of the MAINBOT hybrid navigation system:

1. The overall plan is created in the topological graph, using Dijkstra's algorithm.
2. The robot navigates locally using local metric maps and a search-based planning algorithm.
   - The global metric planner integrated in MAINBOT generates a path from the current position to a desired goal by combining a series of short, kinematically feasible "motion primitives". Planning is done in x, y, and theta dimensions, resulting in smooth paths that take robot orientation into account. This is especially important for RobucarTT robot as it has nonholonomic constraints (due to its Ackerman configuration).

   - The local metric planner can be seen as a controller that drives a mobile base in the plane.

- An execution component called move_base links the global and local planners to achieve the metric navigation.

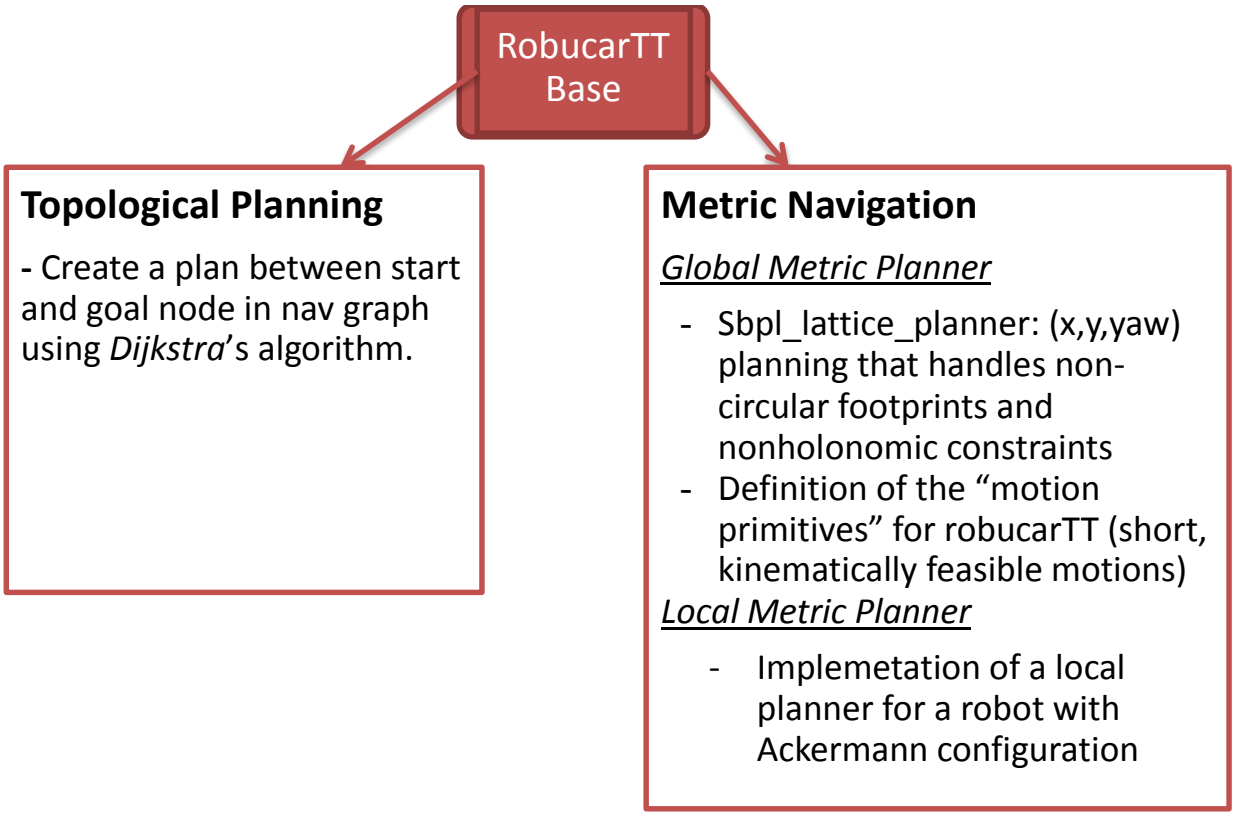


Figure 13: Hybrid navigation in MAINBOT

The local metric planner implemented in MAINBOT proposes a series of forward-and-curve motions and scores them based on how close they follow the path, how far they are from obstacles, and how close they reach the final goal (with adjustable weights for all parameters). The series of forward-and-curve motions have been carefully selected taking into account the kinodynamic constraints of the RobucarTT robot to ensure that the robot is able to follow the global metric plan.

Since the local metric planner adopted scores a series of motions using a metric that incorporates the proximity to obstacles, the obstacle avoidance ability is incorporated into the local planner.

Once the algorithms were tested in simulation, the system was tested using a mockup and finally deployed in the real scenario for validation.

Figure 14: MAINBOT complete Ground robot with the mock-up

Figure 15: MAINBOT complete Ground robot in VALLE plant

Ground platform main characteristics

Specifications	Value	Notes
Using	Outdoor	
Obstacles	250mm, steps	
Ground clearance	280mm	According to the load
Slope	16° without payload 45° without payload (max 60s)	
Banking	45° without payload	
Kinematics	4 independent driving wheels, 2 wheels per axle and 2 guiding steering	
Weight	About 350kgs without payload	
Maximum payload	150kgs	
Maximum speed	2.7m/s / 10km/h	
Dimensions (L x w x h)	2300 x 1365 x 740mm	
Autonomy	8h	
Battery	4 sealed battery 12V-150Ah, 48 VDC – 7kWh	
Main tension	54V fully charged 45V empty	Rated tension : 48V

Extra power supply	DCDC 24V-10A / DCDC 12V-5A / DCDC 5V-5A	
Monitoring of the batteries level	Intelligent digital monitoring system interfaced with PURE	
Protection	IP65 motors and directions IP54 electronics	IP65: Protected against water splashes from all direction by hose (NF EN60529) IP54: Protected against water splashes from all direction (NF EN60529)
Humidity	0-90% without condensation	
Temperature	Functioning : 0°C +50°C / Storage : 0°C +50°C	Integrated sensor for temperature of controller monitoring
Embedded controller (cbn)	1 CE Board (Emtrion HICO 77-80) running PURE software	
Integrated sensors	Localization sensors: Odometry, Gyro and DGPS Security sensors: Laser in front, US and bumpers in front and back	
Working status indication	3 colors light signal integrated	Activation available through PURE
Interface with PURE	Ethernet (UDP protocol)	
Control panel	Manual emergency stop, Wireless remote control stop, Brake releasing switch, Main power switch, Charger connectors	
Mechanical interface	Mechanical support for the arm	

Specifications	Value	Notes
Usage	Outdoor	
Kinematics	6 independent axis	Axis 1,2,3 and 5 have mechanical brakes when power is OFF
Weight	42 kg	
Maximum payload	8,1 kg	
Maximum radius covered	1124mm	Extended from 989mm for the standard version
Main power supply	48 VDC @ 30 A	
Protection index	IP65	
Humidity	0-90% without condensation	
Temperature	Functioning : 0°C +50°C / Storage : 0°C +50°C	
Embedded controller	EMTRION HiCO.SH7780-SBC	
Integrated sensor	Optical encoder on each axis / Magnetic position limit switch	
Interface with PURE	Ethernet (UDP protocol)	On-board UDP server

Table 1: Main characteristics of the redesigned arm

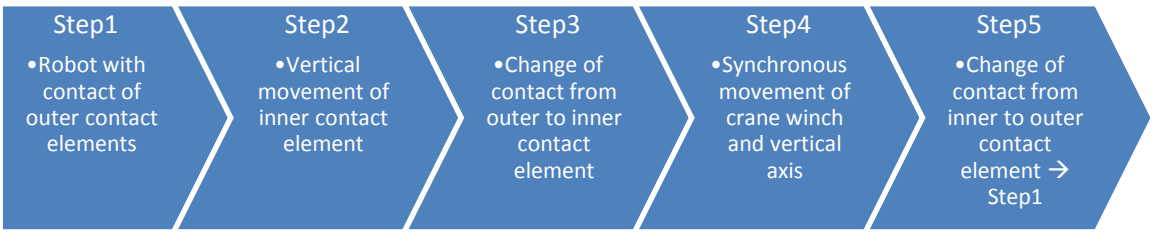
1.1.3.4.2 The climbing robot

The robot is designed for the inspection of vertical structures and is deployable at different assets of the plant. The realized prototype of the climbing robot is capable to inspect the receiver tubes of the central tower of a concentrated solar power plant.

The MAINBOT climbing robot main features are:

- Robot weight: ~280kg
- Robot dimensions: 2,3mx1,6mx0,8mHigh payload (only limited by crane)
- Overcoming obstacle (because of stepping mechanism)
- Adaptable to different surfaces: material and structures (exchangeable and adjustable contact elements)
- Accurate tool (sensor) positioning thanks to servo controlled motion system
- Fully and semi-automated operation modes with web-based UI interface
- Synchronized movement of robot and supporting crane

The robot comprises a stepping mechanism with a variable step size. The load of the robot is carried by crane on top of the tower. The robot is horizontally secured by its contact elements to avoid swinging of the system. The robot is in contact to both neighbouring panels to have the entire panel free for the inspection. The step width is greater than the robot height through the telescopic mechanism. The stepping kinematic is also used for the sensor movement. The following chart describes the climbing procedure of the robot:



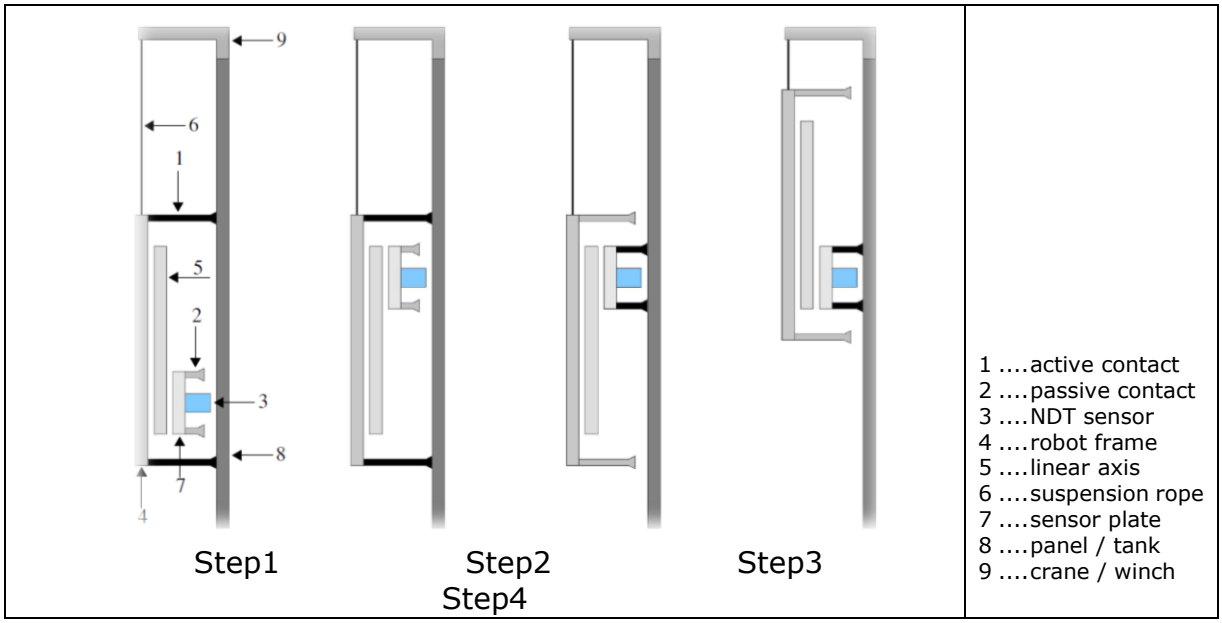


Figure 16: Stepping procedure of climbing robot

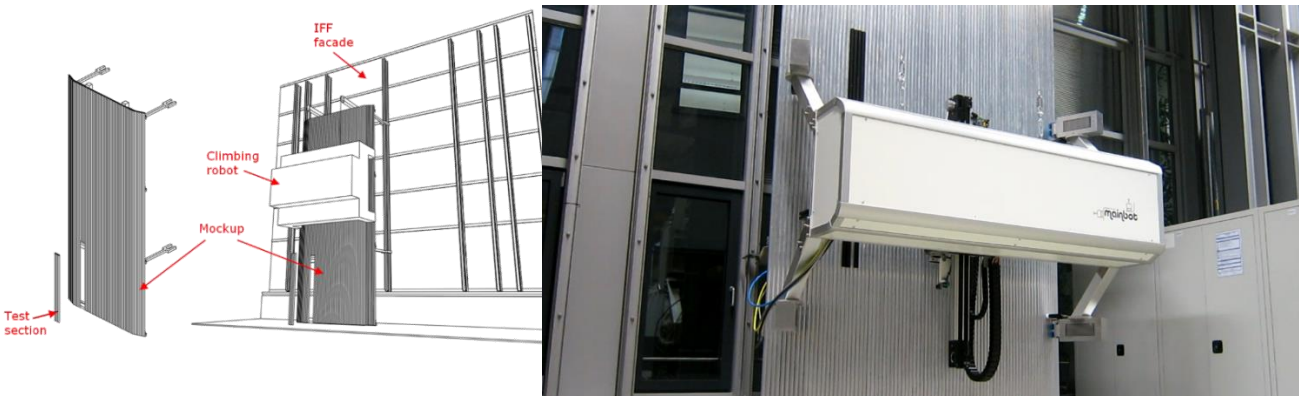


Figure 17: Schematic and real views of GEMASOLAR Mock-up at IFF facility

The contact with the absorber tube needed for Eddy Current based inspection (GEMASOLAR tower) is realized with vacuum grippers arranged at contact elements (see Figure 30). There are four outer contact elements at the robot frame with horizontal adjustment functionality and one central contact element at the sensor head with vertical adjustment functionality.

The outer elements are in contact at the neighbouring panels during the inspection phase. Therefore the vacuum grippers are automatically aligned with the tubes in a two stage contact process. Soft bumpers at the elements ensure a collision free movement of the robot to protect the tube surface.

The central contact element can move in XYZ-direction with respect to the robot frame. The element is in contact during the vertical robot movement. The vertical deflection of the crane winch and the vertical robot axis is measured with a wire sensor. This position signal is used to synchronize winch and robot.

A simulation of docking the robot kinematic at the panels was carried out. Thanks to it, it was possible to predict the robot behaviour during the process of getting in contact to the panel after lowering the robot down with the winch (docking process). Further outcome of the simulation was the position of the robot relatively to tube panels in different initial conditions (e.g. angular and translational displacement in robot position caused by lateral wind forces).

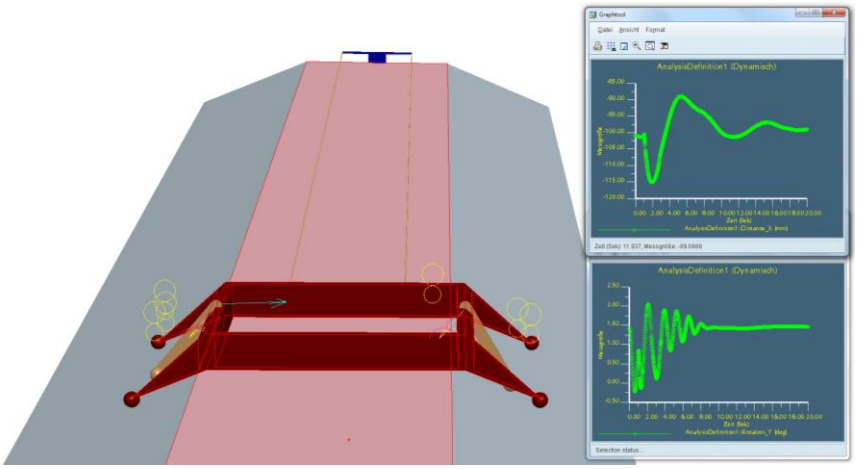


Figure 18: simulation of docking process with analogous robot model

1.1.3.5 The robotic inspection systems

In order to carried out the operations defined for both scenarios non-destructive testing technologies have been adapted for robotic integration.

To control all the elements in the system a general Manager has been developed. It is in charge of the high level planning/scheduling/monitoring of maintenance robot activities by means of the following capabilities:

- Task Planning: It is mainly responsible for the interpretation of the mission the system has to perform. It decomposes a complex task into its executable parts (in terms of navigation and manipulation commands). The Manager generates elementary operations and it is responsible of setting goals to the robotic components.
- Supervision/Diagnosis: aims at monitoring all the system status and to provide fault tolerance capabilities.
- Scheduling: aims at coordinating the activity of the different elements during robots missions.

The different missions have been modelled as state machines diagrams.

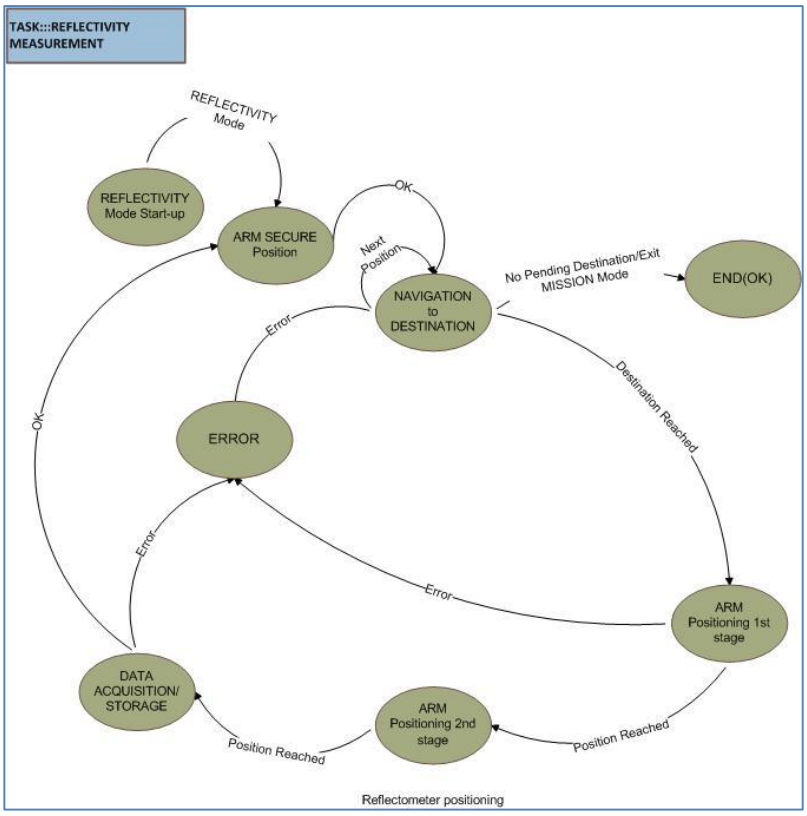


Figure 19: Task: Reflectivity use case state machine

Robotic Operating System, ROS, has been selected as framework on top of which the rest of modules are integrated. Next picture shows the main modules integrated in this framework in the case of the ground robot.

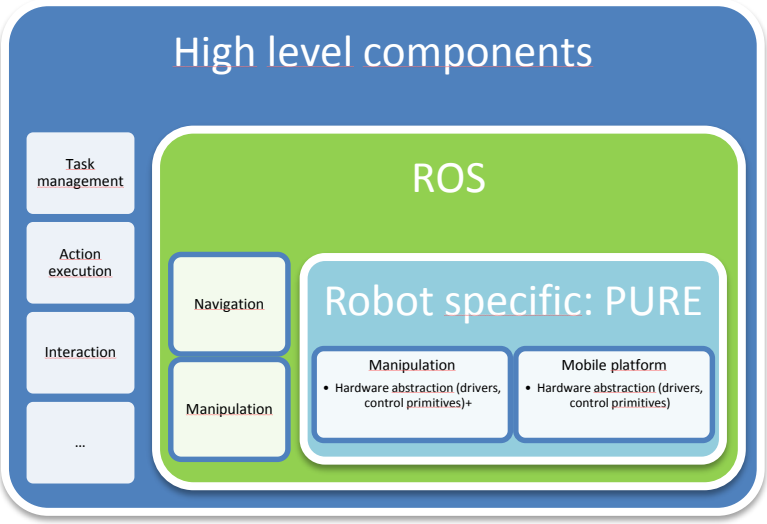


Figure 20: ROS integration into the architecture

The control architecture and relationships among the modules are shown in Figure 21.

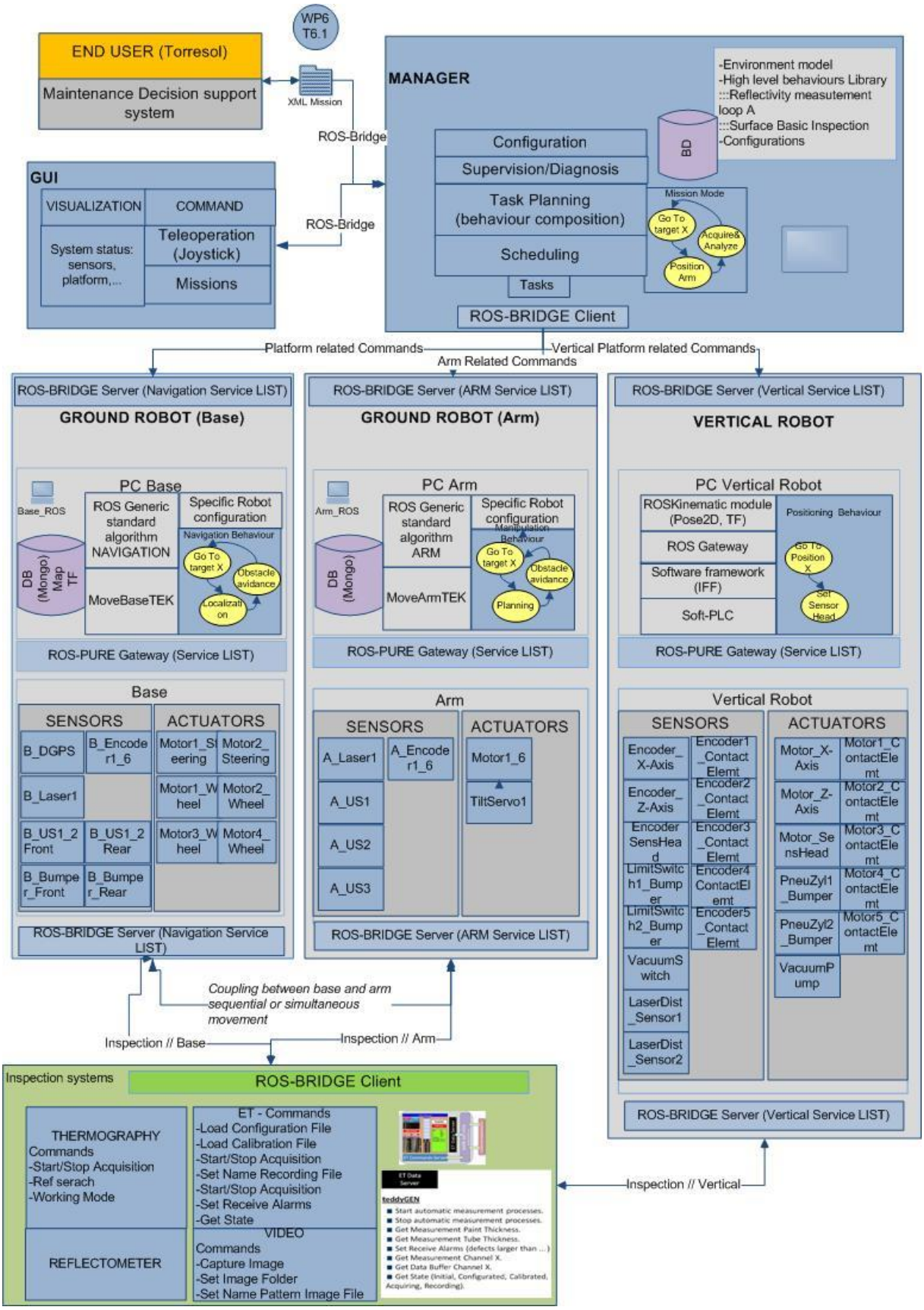


Figure 21: System architecture overview

All relevant information and robot commands are accessible through a Graphic User Interface (GUI) developed using web technology:

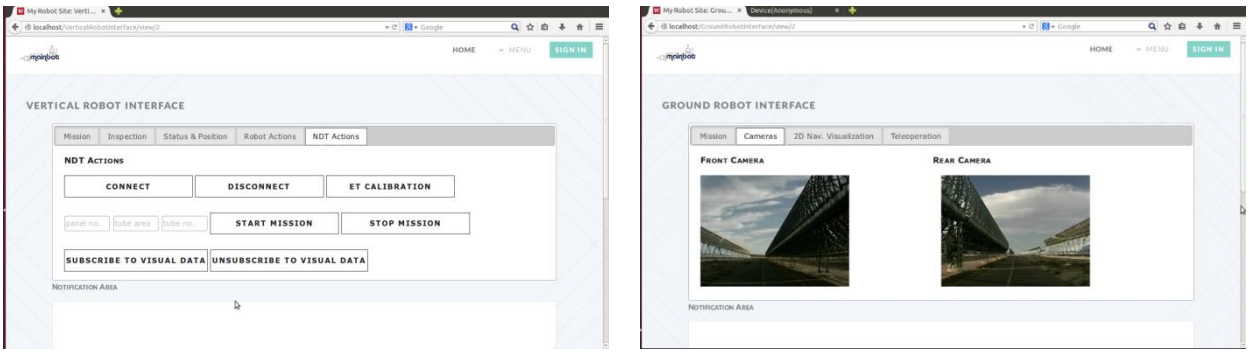


Figure 22: Two screenshots of MAINBOT GUI

1.1.3.5.1 Reflectivity measurement

A toolholder has been designed to hold the reflectometer and carry out the measurements safely (there is physical contact between the device and the mirror). It includes a metallic frame, 3 ultrasonic sensors for accurate estimation of the pose of the tool with respect the mirror and the piston that activates the button for data recording.

Figure 23: Reflectometer holder detail

In the real operation, the platform navigates up to the mirror that has to be inspected, the tool (holding the sensor) is positioned perpendicular 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 to control the trajectory.

Figure 24: Reflectivity measurement operation and detail of the contact

1.1.3.5.2 Vacuum loss and broken mirror detection

Thermographic images are used to monitor the presence of broken mirrors and identify any vacuum loss in the tubes.

The strategy is based on the fact that when a loss of vacuum exists there is a high gradient of temperature between different sections of tubes.

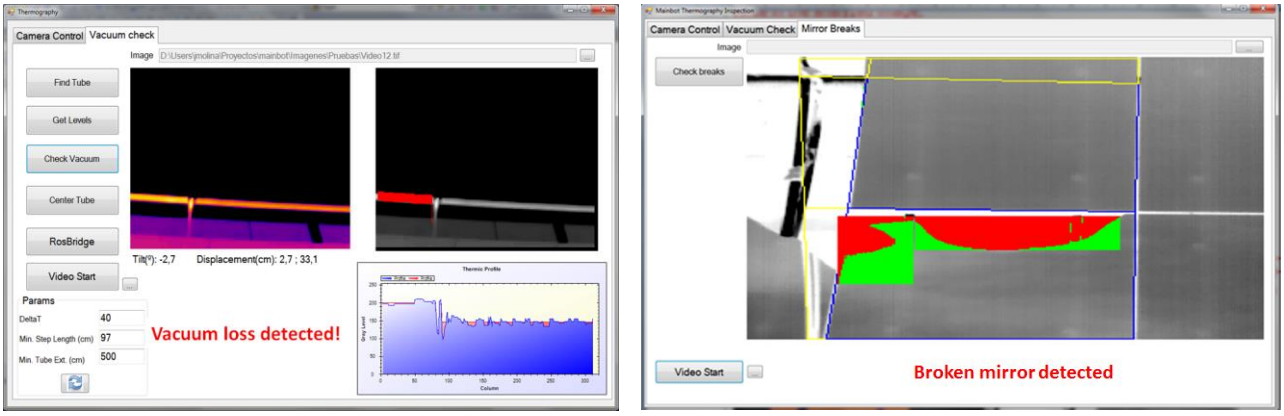


Figure 25: Loss of vacuum and broken mirror analysis application

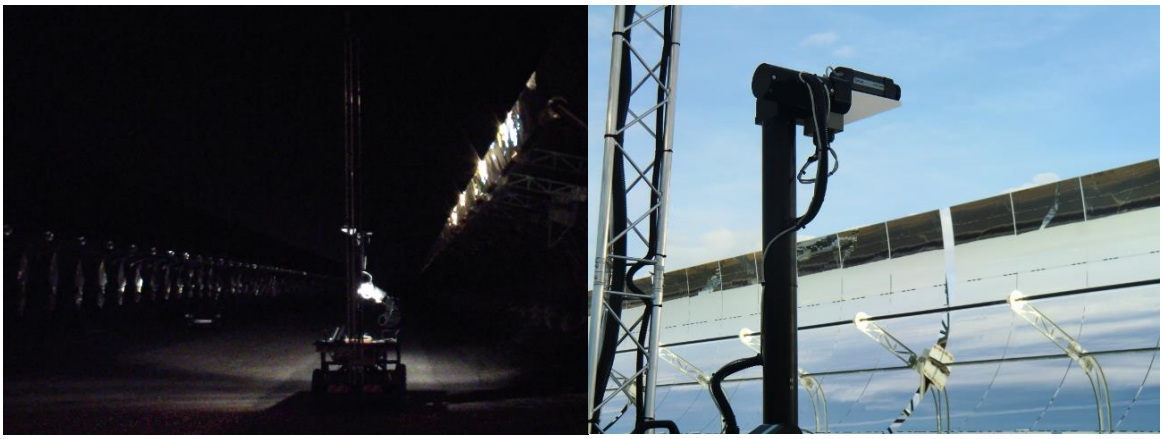


Figure 26: Thermography based inspection in VALLE at night and daylight

1.1.3.5.3 Leakage detection

Any HTF leakage creates a gas flow; the algorithm is based on the detection of this gas flume over a series of frames. Leakages can be detected with infrared cameras sensitive in the wavelength where the gas has absorption peaks. With the appropriate infrared camera leakages would be seen as smoke.

Without the appropriate thermography camera it is not possible to validate the algorithm in a real environment. To overcome this issue, it has been used ammonium hydroxide and acetic acid, non-harmful gases, with an absorption peaks in the range where the available thermography camera can work.

The behaviour was tested at ambient conditions, the results are shown in next figures.

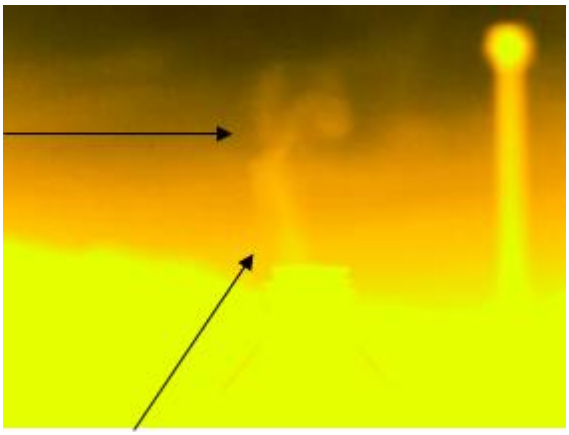


Figure 27: Ammonium hydroxide test, arrows indicate the emanated gas in the thermal image

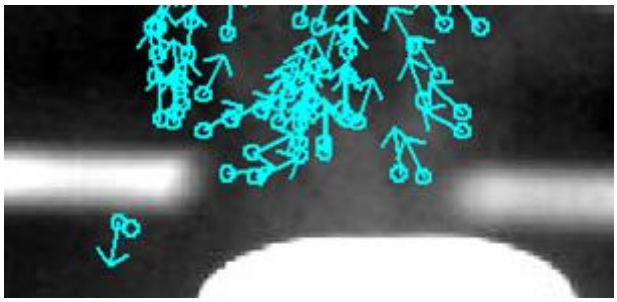


Figure 28: Optical flow detection based on thermal images

This solution can be extended to other gases by using other suitable, even expensive, cameras working in the wavelength range of the gas.

1.1.3.5.4 Surface and inner condition assessment

Two non-destructive techniques (2D vision and eddy current) have been integrated in the climbing robot for the GEMASOLAR scenario to assess the degradation of the receiver tubes.

The coating thickness (μm) is measured by Eddy Current Technique (ET) to detect reductions in the performance of the heat transfer. Furthermore the tube thickness (<3-4 mm) is inspected with ET to detect internal degradation of the tubes.

The theoretical foundation of Eddy current technology is shown in next figure:

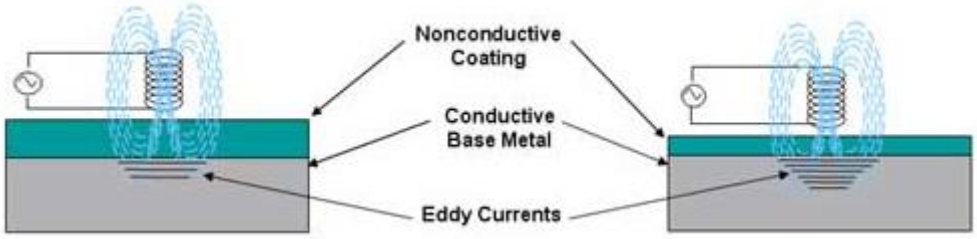


Figure 29 Eddy current measurement of coatings

By means of a camera and the proper lightning system (Visual Inspection Technique VT) external loss of coatings (5x5 mm) are detected.

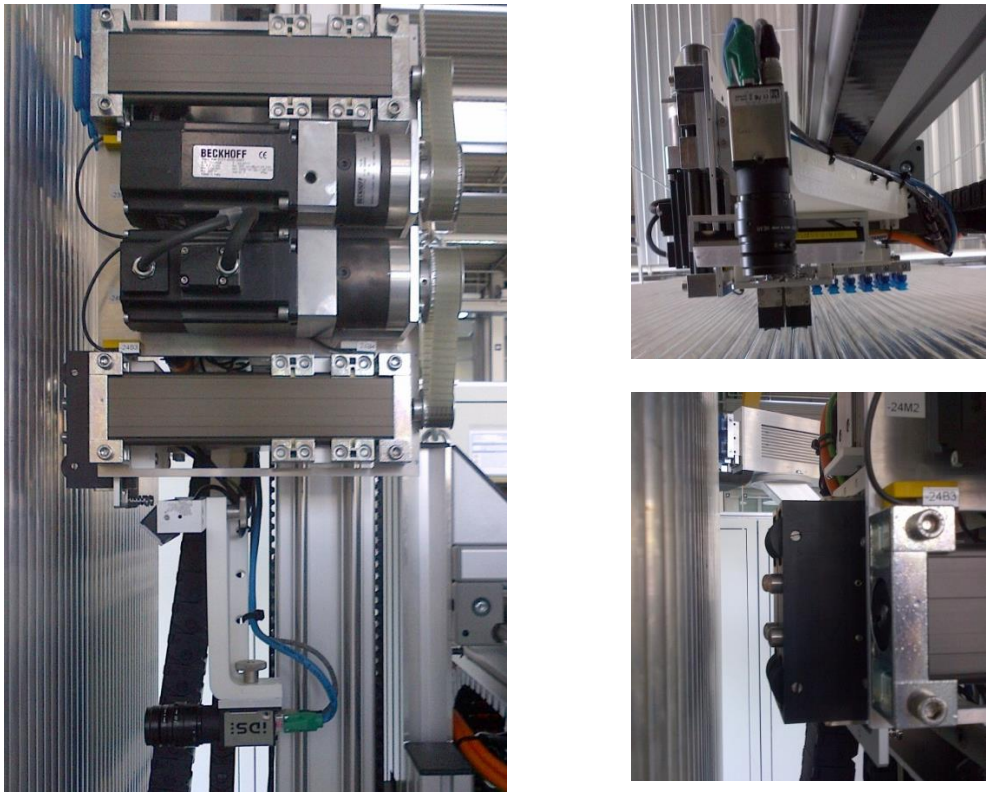


Figure 30: NDT integration and central contact element

Coating thickness measurement

Coating thickness is measured with high frequency eddy current sensors. A reduction of theoretical thickness means coating degradation. ET signals are processed and compared with calibration tubes. System calibration is performed automatically and internal algorithms convert ET signals (vertical and horizontal component) into thickness measurements (including internal filters to reduce noise and to stabilize the signal). Figure 31 shows that coating layer is not uniform along the tubes.

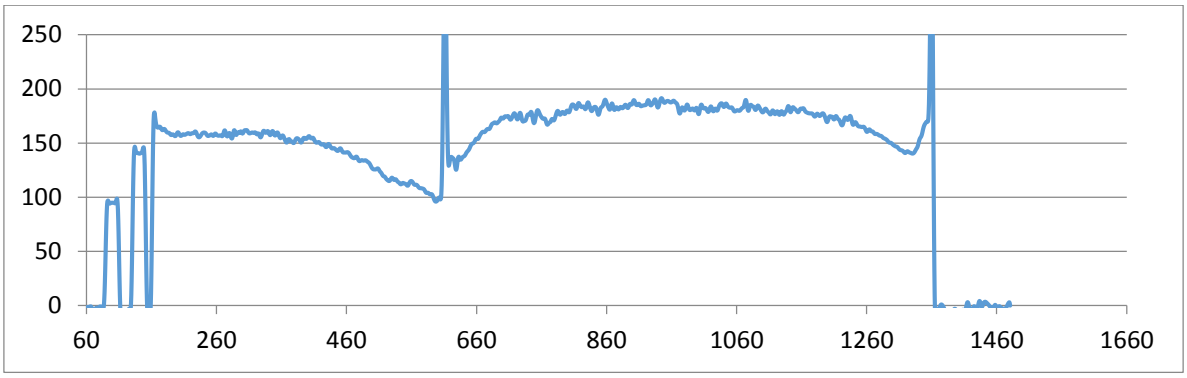


Figure 31: Coating thickness measurement

Coating loss detection:

The complete loss of coating in the tubes is detected by visual inspection. Images are recorded and automatically processed to detect and size existing coating defects. During the calibration process, the area of interest is selected and distortion correction is performed specially in the horizontal axis, using square artificial calibration defects.

Id	Type	Panel	Tube	Area	Magnitude (mm²)	X (mm)	Y (mm)	Width (mm)	Height (mm)
2	Scratch	1	1	1	94.6781	51.41	197.62	9.13	10.37

Figure 32: Visual Inspection. Detection of coating losses

<u>Tube thickness measurement:</u>

Tube thickness is measured with low frequency eddy current sensors to achieve a higher penetration in the material. On-line data processing is required to separate the signals from internal artificial defects from the coating influence. To do that, data is recorded at two frequencies: “f”, the optimum low frequency to inspect tube thickness and at a higher frequency, “2f”, to detect surface defects. Both signals are combined applying several algorithms that eliminate undesirable effects, providing clean records in which corrosion (thickness measurement) can be directly estimated by comparing with the calibration tubes. System calibration is performed automatically and internal algorithms convert ET signals (vertical and horizontal component) to thickness measurements.

1.1.3.6 Final conclusions

Both prototypes have been successfully.

- The climbing robot based inspection in a realistic mock-up that simulates the GEMASOLAR scenario, in particular the receiver tubes at the top of it. This evaluation could not be performed in the real tower due to operational difficulties and potential risks of affecting the normal activity of the plant.

- The ground robot based inspection in the real solar field, in VALLE.

Figure 33: Inspection ground robot navigating in different conditions

All planned operations have been tested and results show that the proposed solution can be deployed in the short-medium term in this kind of plants and similar applications can be customized for other scenarios.

Some improvements have been already identified (see next section).

1.1.4 Potential impact, dissemination activities and exploitation of results

During the project development, Spanish government has introduced important regulatory changes in the Electrical Market, concerning to payment regime and bonus system that affect to Renewable Sector. In particular, this change affect seriously to the Thermal Solar plants in long term, obviously Project Finances were realized according to previous market regulation. Due to this economical restrictions and the impossibility to compete with Conventional Energy Companies (€/kwh), O&M companies must be adapted to this new scenario and no intensify the activities to guarantee the highest level of efficiency in this kind of technology resulting in a lower investment in some O&M specific activities

Probably this is a transient regulation that will change once the economic situation improved but, at present, it means that it is not foreseeable the real deployment of this kind of solutions in Spanish thermal solar plants while the current bonus regulation is active. For this reason, it has to be explored the potential interest of the proposed solution in other countries wherein there are running or under construction similar plants.

In fact, a recent analysis carried out by CSP Today has reinforced the appropriateness of the use cases selected. This study about the failures in thermosolar plants clearly identifies the elements that are prone to failure. They correspond to those that have been selected in MAINBOT (see those signalled with the red circle)

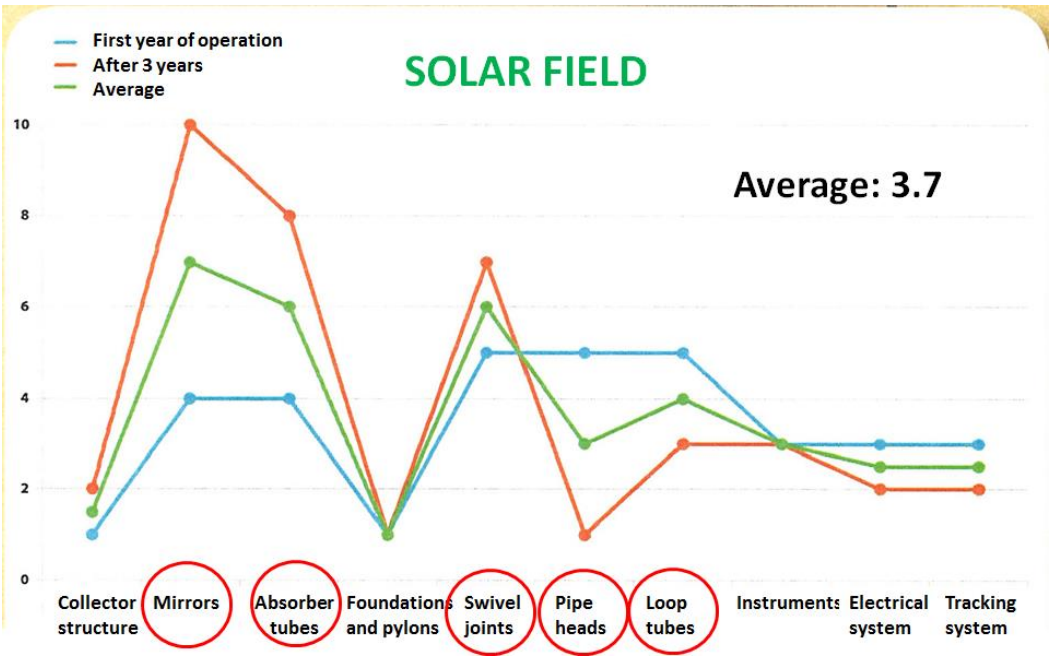


Figure 34: Frequency of failures in a thermosolar plant. Source CSP Today

The consortium believes in the real economic benefits that the proposed technology can bring to industrial companies running extensive plants beyond the CSP sector.

As a consequence an analysis of exploitable results and mechanisms to market them has been carried out.

In summary 17 exploitable results have been identified (see Table B2). Moreover the consortium has developed two Business models to market two different categories of results.

1. The specific prototypes that have been developed and tested for Concentrated Solar Plants (CSP).

   Even if they have been tested in realistic (Climbing robot) and real (ground) scenarios, the consortium considers that they still demand a further development to achieve the need degree of robustness and 'Industrial category': Some of this developments are:

   - New design of the ground robot that takes into account protection against environmental conditions.
   - Introduction of break for axis 4th of the 6 DoF arm.
   - Increase the reachability of the arm, by increasing some axis length
   - Introducing more powerful motors in the arm to avoid working in the limit of their capacity
   - Increase the NDT sensors in the climbing robot to reduce the time required to inspect the absorber tubes
   - An additional laser distance sensor at the lower end of the robot and an inclination sensor on-board to detect the panel ends and to determine the correct robot inclination
   - Additional validation process in real working conditions should be carried out for the climbing robot.

   ROBOSOFT, has been identified as the natural partner to develop this Business Model:

   - Its core business is the development and commercialization of Mobile Robotics
   - It has an engineering team in robotics and known how to deal a product to the customer.
   - The company has expertise in robotic technology integration.
   - ROBOSOFT has its own assembly facilities.
   - They operate worldwide
   - ROBOSOFT has been the provider of two of the robotic units (the ground wheeled robot and the robotic arm) and has experience on climbing robots (they have developed their own cleaning climbing robot). Moreover it is capable of customize the actual system to meet different inspection tasks and then cover more potential applications.

   In this context IFF, TEKNIKER & TECNATON will be KEY providers of ROBOSOFT and it will be necessary to reach a long term agreement for this relationship in terms of cost in hardware, software and Licenses

2. The knowledge generated and gained during the project execution.

   After 3 years of work, the 5 partners have gained a common and better understanding of the needs in this kind of applications, they have been able to work together in order to achieve valid results and they have developed innovative solutions to answer to these requirements. The proposed value proposition is to exploit this knowledge in form of an engineering service that can be implemented in different ways.

   TECNATOM, as an engineering company providing maintenance solutions to the industry, will be in charge to developing this Business Model:

   - One of its core businesses is the provision of Maintenance services to big companies. Therefore, they have a good knowledge of the O&M business in different sectors. In particular, TECNATOM is present in several Spanish thermosolar plants providing in-service inspection of collector tubes and steam generator tubes, among others.

   - Moreover, TECNATOM has developed Maintenance Manuals for several Spanish solar plants. These Manuals define organization and management of all Maintenance activities to be carried out in the plant, based on operating conditions (e.g. required periodical inspections), plant integrity (e.g. following up evolution of existing defects, etc.), etc. TECNATOM has also developed a Software to manage all these issues ("Inspection Manager"). This Software can be customized and integrated with plant Control Software.
     The software collects and records historical data to assess plant performance and efficiency (though advanced data bases that include detailed drawing and characteristics of the plants. The new advantages regarding automated inspection processes developed in MAINBOT could be integrated as part of the Maintenance Plans and coordinated with Plant Operation.

   - They have engineering capabilities to develop inspection systems (it is in fact one of their business), as it has been the case in the inspection of receiver tubes in the climbing robot scenario.

   - They have industrial experience in the integration of NDT and robots

   - They have experience in the design and development of control rooms for plant operation, simulators for training, etc. for nuclear and solar power plants.

   - They operate worldwide through TECNATOM's Group companies established in Spain (TECNATOM, S.A., Ibercal and Sertec), in Brasil (TECNATOM do Brasil), in China (CITEC), in Arabian Emirates (nuclear control rooms simulators and training), etc. Current alliances with companies such as General Electric,

Westinghouse, etc., open new opportunities and markets worldwide (USA, Japan, Mexico, Argentina etc.).

In both cases there are several steps that have to be done to implement the proposed exploitation mechanism:

- Identification of further activities to produce industrial scale products out of the two prototypes developed in the project to achieve a higher TRL
- Analysis of customization needs for the general solution
- Definition of common developments applicable to different maintenance activities (to be developed by ROBOSOFT, IFF, TEKNIKER and TECNATOM):
    - Control interfaces.
    - Robotic platforms (including navigation capabilities, sensors, etc.)
    - Robotic tools.
    - Communication protocols.
    - Task planning capabilities.
    - Portable/autonomous NDT instrumentation from a HW/SW point of view
- Creation of marketing material. Dissemination of the results of the project in industrial forums, specialized congresses and trade fairs
- Contact with main CSP and O&M companies to provide detailed information about the project results
- Deeper analysis of maintenance activities in different fields (type, schedule, etc.).
- Searching for follow-up financing for the pre-commercial development
- Establishment of a Commercial and Exploitation agreement between the partners

MAINBOT has used three 3 demonstrators as the main mechanisms for demonstration purposes:

- The mock-up of the GEMASOLAR scenario and the robot prototype at IFF facilities in Magdeburg, Germany.
- The mock-up of the VALLE scenario and the ground robot prototype at TEKNIKER facilities in Eibar, Spain.
- A Virtual reality environment set-up at IFF

Figure 35: Permanent mockup of parabolic trough CSP at TEKNIKER

Figure 36: Permanent mockup of central tower CSP at IFF

Figure 37: simulated Central Tower CSP at Elbe Dom mixed reality laboratory, IFF

These facilities make it possible to have permanent demonstrators in which all technologies can be presented to any interested company.

On the other hand TEKNIKER is taking part in the STAGE (Scientific and Technological Alliance for Guaranteeing the European Excellence in Concentrating Solar Thermal Energy, FP7 609837) project (https://www.stage-ste.eu/index.php)
The objectives of the project are twofold: (1) explore and develop new concepts and technologies suitable for distributed generation (power, industrial process heat, and solar heating/cooling) using line-focusing solar collectors; (2) development of techniques to perform dynamic solar field testing of large solar fields, new methodologies for on-site characterization of large line-focus solar collectors' fields, and solutions to improve the operation and maintenance of line-focus STE plants.

TEKNIKER has offered the MAINBOT prototype to the rest of the consortium for any activity related with automating inspection.

On the other hand the project has used 'standard' dissemination mechanisms, as flyers, press releases, presence in media, congresses and scientific publications. This is an ongoing process beyond the end of the project. In fact, the validation of results has been achieved very late in the project, so the preparation of papers and publications based on these results will take some time. This is the case of the papers that have been already identified for publication:

- Robotized inspection of vertical structures of a solar power plant using NDT techniques (to be submitted to Robotics Journal)
- Mobile manipulation for inspection in extensive industrial plants (to be submitted to International Journal of Advanced Robotic Systems)

- MAINBOT: Nueva generación de robots de servicio para la inspección y mantenimiento de centrales termosolares (to be presented in the congress organized by the Spanish association of non-destructive testing, AEND)

A complete list of actions is presented later in this document.

1.1.5 Project contact

More information is available in www.mainbot.eu, or can be requested by writing to mainbot@tekniker.es or to the coordinator inaki.maurtua@tekniker.es

The list of participants and their contact links are available through the project website