Autonomous Robotic System with Tunnel Inspection Tool Positioning

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Abstract –

This paper presents the ROBO-SPECT European FP7 project, funded under the ICT-2013.2.2 programme on Robotics use cases & Accompanying measures. The main objective of the ROBO-SPECT system is to provide a robotized, faster and reliable alternative to manual tunnel structural inspection and assessment. Physical developments include the design and implementation of a multi-degree-of-freedom (MDoF) robotic system, which uses a mobile vehicle to advance along the roadway, an extended crane capable of reaching the most commonly found tunnel geometries, and a robotic arm for positioning a specifically designed ultrasonic sensor (US) Inspection Tool with high accuracy. A semi-supervised computer vision system to detect tunnel defects, a Ground Control Station (GCS) to provide a Human-Machine Interface (HMI), and an Intelligent Global Controller (IGC) to command the robot and manage communications between the different parts have also been developed.

An overview of the fundamental aspects of the project architecture and design will be detailed. In addition, the developed and implemented algorithm for positioning the Tunnel Inspection Tool on detected cracks shall be presented. Finally, experimental evidence to validate the functionality of the ROBO-SPECT system in a real motorway tunnel with ongoing traffic will be provided.

Keywords –
Automation; Control of Robotic Systems; Tunnel; Inspection; Maintenance;

1 Introduction

When facing existing civil infrastructures, one of the greatest challenges that engineers may find is its inspection and assessment in order to to ensure that bridges, roads, pipelines and tunnels remain in safe condition and continue to provide reliable levels of service [1], [2]. The structural performance of tunnels is time-dependent because of the damaging process induced by natural and artificial impacts, inadequate maintance or the simple effect of ageing.

Water supply, metro, railway and roadway tunnels have increased in both total length and number, and will continue to do so on a global scale. Some tunnels still in service were constructed over 50 years ago, and many have exceeded their intended design service life [3]. Only in Europe in 2002, the overall length for operational transportation tunnels had grown up to 15000 km [4].

Tunnels are characterized by humidity, dust and absence of natural light. Inspection and maintance operations are commonly performed by human operators, taking time and expertise. Additionally, the human factor combined with the unfriendly environment could lead to lack of guarantee regarding quality control.

These facts highlight the need of automated, cost-effective and exhaustive solution to inspect tunnels that prevents such disasters. In this work, the final integrated ROBO-SPECT system is presented, followed by the safe positioning algorithm of the Ultrasonic Sensors (US) inspection tool on a detected crack. Finally, experimental evince, timing and accuracy results and conclusions are also presented.

2 The ROBO-SPECT European Project

ROBO-SPECT is a research project co-funded by the European Commission under the 7th Framework Programme (FP7) ICT-2013.2.2 on Robotics use cases & Accompanying measures. The project ran between October 2013 and October 2016 and was composed by a Consortium of 12 partners. The overall objective of ROBO-SPECT is to design and implement an automated, faster and reliable tunnel inspection robotic system that inspects cracks and other defects of the tunnel lining on one pass without interfering with tunnel traffic (Figure 1). The system also includes a detailed structural assessment software.

The specific objectives of this project are the following [5]:

- Minimize the use of tunnel inspectors. Presently, the maintenance consists in visual inspections, which is labour intensive and subjective.
- Improve the unhealthy and unsafe working conditions of tunnel inspectors.
- Decrease inspection and assessment costs.
- Increase the safety of passengers.
- Increase the residual lifetime of existing tunnels.
- Decrease the time tunnels are closed for inspection. The impact of this is significant for tunnels with heavy traffic volume.
- Provide better quality, objective, timely data and an improved knowledge of the tunnel lining.

Figure 1. ROBO-SPECT is an FP7 European project to design a fully autonomous tunnel inspection robotic system.

In summary, the needs which ROBO-SPECT addresses are the following:

- High cost of new tunnel constructions (need for inspection, assessment and repair of existing).
- Transport demand is highly increasing and cannot cope with the rate of transport infrastructure and high tunnels uptime.
- Inspection and assessment should be speedy to minimize tunnel closures or partial closures.
- Engineering hours for tunnel inspection and assessment are severely limited.
- Currently tunnel inspections are predominantly performed through scheduled, periodic, tunnel-wide visual observations by inspectors who identify structural defects and categorize them manually (manual, slow and labour expensive process).
- Un-reliable classification of the liner conditions and lack of engineering analysis.

3 The ROBO-SPECT System Design

The ROBOS-SPECT system is composed of four different components that allow the complete inspection and assessment of the tunnel, aimed at providing all the functionalities to the final users. The first component is the robotic system, which incorporates all the different components needed to perform the tunnel lining inspection. The second component is the Ground Control Station (GCS), that monitors the robot mission and communicates with the robotic system. The third component is the Control Room (CR), that is the site where the data gathered during the inspection is used to generate a complete assessment report about the tunnel state. Finally, the Intelligent Global Controller (IGC) communicates with the different subsystems and manages the execution of all the tasks.

3.1 Robotic System

The ROBO-SPECT robotic system design is based on TUNCONSTRUCT European Project (FP6) [6] system, which used a similar vehicle, crane and robotic arm configuration.

The robotic system is composed by an industrial mobile vehicle capable of extending an automated crane to the dimensions commonly found in metro and roadway tunnels. It is equipped with a high precision robotic arm that positions the ultrasonic sensors (US) inspection tool on cracks on the tunnel lining to perform measurements. A vision system to detect cracks on-line and other defects, like spalling [7] and efflorescence [3] offline, and a 3D laser profiler to detect deformations on the tunnel lining are also part of the system. An additional set of cameras are placed on the crane and an IP camera is attached to the tip of the arm for an extra teleoperation mode.

Figure 2 depicts the actual design of the robotic system and the different components that shall be described in detail.

3.1.1 Mobile Vehicle

The mobile vehicle is able to autonomously navigate on one line of the roadway maintaining a constant parametrized distance to the tunnel wall with ongoing traffic on the other line.

The navigation is based on Simultaneous Localization and Mapping (SLAM) and is performed using a dedicated navigation sensor situated in the front part of the vehicle and a set of reflective beacons that are placed on both sides of the roadway. In order to localize the robot with high precision and simultaneously create an accurate 2D map of the navigated section, a minimum of 3 beacons need to be detected at the same time. This map is used to improve navigation precision in subsequent inspections.

The mobile vehicle is also capable of avoiding collision using two 2D range laser sensors, one in the front and one on the back of the vehicle.

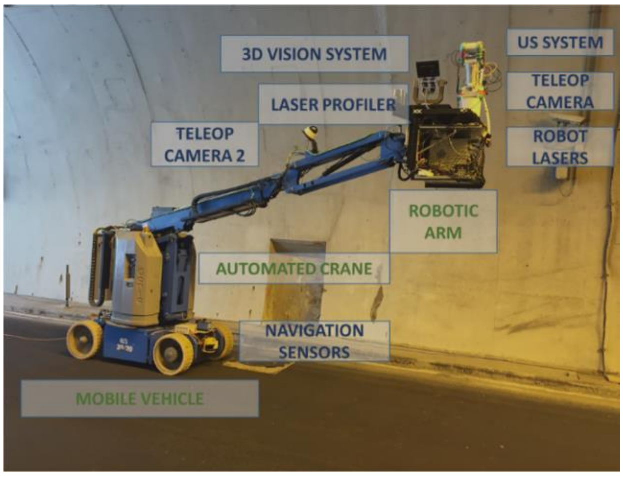

Figure 2. ROBO-SPECT Robotic System is composed by a mobile vehicle, an automated crane, a robotic arm, an US inspection tool, a vision system, a 3D laser profiler and teleoperation cameras.

3.1.2 Automated Crane

The crane has been sensorized, including additional elements such as encoders inside the joints to control the crane tip position and orientation. The joints of the crane are equipped with special brakes to minimize the oscillation and vibration. The crane mission is to position a redesigned platform with the robotic arm equipped with the US inspection tool, the 3D vision system and the 3D laser profiler to gather inspection data. The behaviour of these components is described below. This platform also includes a 2D laser sensor to provide 3D point cloud scans of the tunnel lining and avoid collisions while moving the crane.

3.1.3 Robotic Arm

The robotic arm chosen for the application is the Mitsubishi PA-10, a 7 Degrees Of Freedom (DoF) industrial manipulator. 6 DoF are needed to provide full position and orientation capabilities and the other one adds obstacle avoidance and correct orientation functionalities. The reachable workspace covered by this high precision robotic arm ranges from a few centimetres to 1 meter approximately from the base to the end-effector of the arm, which is limited by basic kinematic restrictions and self-collisions. Figure 3 depicts the selected robotic arm, along with the vision system and the 3D laser profiler.

The robot has 10 kg load capacity which is enough to support the ultrasonic sensors inspection tool located at the tip that performs measurements on cracks inside the tunnel lining, the IP camera placed below it that monitors the process and provides visual feedback in case of using the safe teleoperation mode, and the 2D robot laser sensor attached to a link of the arm which scans the surroundings of the detected crack.

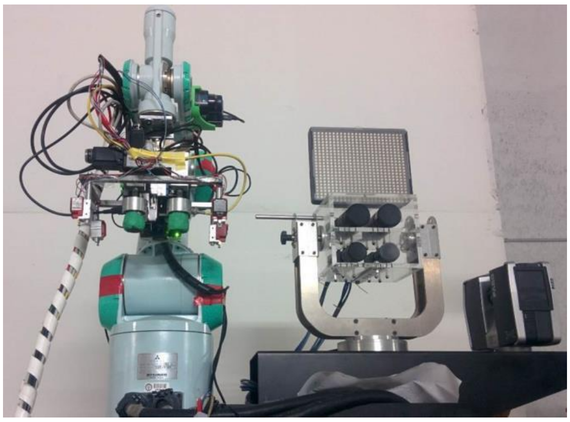

Figure 3. The ROBO-SPECT components attached to the crane: the robotic arm, the vision system and the 3D laser profiler.

3.1.4 Vision System

The ROBO-SPECT vision system located on the crane platform is equipped with a pan&tilt mechanism designed to orientate two pairs of RGB cameras that detects defects inside the tunnel lining and takes stereo images of detected cracks. In order to operate with the proper lighting conditions an on-board lighting system is also added. A highlighted fact about the vision system is its needs to be positioned at a determined distance to the wall, given by the camera focal length. The first pair of cameras are designed to be able to identify a set of different defects commonly found in tunnels such as spalling, efflorescence, etc. These defects are detected using machine vision techniques, such as Convolutional Neural Networks (CNN) [8] trained with real images of tunnel defects. These cameras are also used to detect cracks in real time and to estimate their 3D positions and orientations. This data is then send to the robot to aproach the crane to the crack surroundings first, and then move the robotic arm to touch the tunnel wall with the US inspection tool. The other pair of cameras are designed to take stereo images of detected cracks.

3.1.5 3D Laser Profiler

Furthermore, the 3D laser profiler chosen is placed on the crane platform to inspect tunnel structural deformation with an accuracy of 2 mm.

3.1.6 Ultrasonic Sensors (US) Inspection Tool

A set of specically designed ultrasonic sensors is attached at the tip of the robotic arm to measure the width and depth of a detected crack while in contact with the tunnel lining. The depth measurement of the crack is done using two piezo-electric ceramic transducers that must be placed on each side of the crack. The method utilized to measure the depth is the well-known Time of Flight (ToF) [9], which is the time a wave is generated on one side of the crack and detected on the other side. Respecting the width measurement, a newly designed fiber-optic sensor is used. The sensor is placed on the crack using a XY positioning stage. When the measurements have been taken, the robotic arm removes the sensors from the tunnel wall, and the inspection continues.

As part of the US Inspection Tool, a rectangular frame with contact sensors on its corners has been attached to the tip of the robot arm (Figure 4). These contact sensors, currently implemented as normally closed push button switches, allow detecting the tunnel wall during the approximation of the ultrasonic sensors, and also for maintaining a stable position of the ultrasonic sensors until the measurements are made.

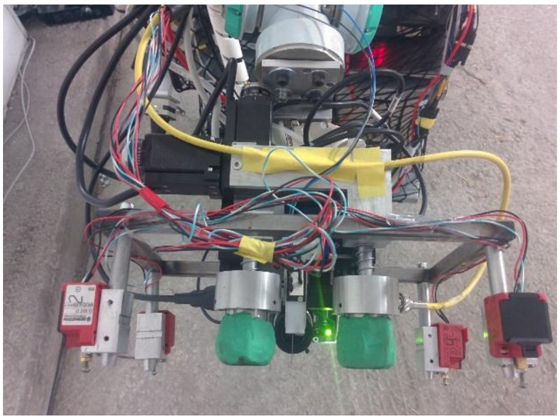

Figure 4. Contact sensors, currently implemented as normally closed push button switches, placed on a rectangular frame allow detecting the tunnel lining for a safe placement of the ultrasonic sensors.

3.1.7 Intelligent Global Controller (IGC)

As the system is composed of several different components that need to be controlled simultaneously, a Intelligent Global Controller (IGC) is placed inside the robot to manage communications with all the parts. All the different components (mobile vehicle, crane, arm, etc) are connected to a local network during the autonomous inspection process inside the tunnel. The software used to communicate is a mixed solution of YARP [10] and ROS [11].

The Ground Control Station (GCS) sends a mission to the IGC in order to command the robot to perform the requested mission. The IGC is able to navigate the robot through the tunnel, indentify when a crack has been detected, and perform the necessary joint movements to place the ultrasonic sensors on the crack and take all the required measurements. The IGC monitors the system state and reports the inspection data gathered and updates the GCS with the state of the mission.

3.1.8 Ground Control Station (GCS)

The Ground Control Station (GCS) is a component outside the robot that is in contact with it during the inspection. This system consists in a standard laptop with Wi-Fi connection to the router installed on the robot. The GCS includes the Mission Manager, a Human-Machine Interface (HMI) that allows the user to define a mission (definition of the path, modes of operation), and contacts with the IGC to start the mission with the defined parameters and to receive the state of the robotic system and the results during the inspection. If connection is lost with the robot, the GCS is able to gather the generated data when established again while the robot continues autonomously the inspection.

3.1.9 Control Room (CR)

The Control Room (CR) represents the site where all the information gathered during the autonomous inspection is processed using the Structural Assessment Tool (SAT). This software tool stores, graphically represents, and processes all the inspection data. The SAT allows the end-user to see the generated maps of the tunnel, data of the different cracks and other defects detected, and their position inside the tunnel, etc. Finally, it produces a complete assessment report of the structural state of the system that is presented to the end-users.

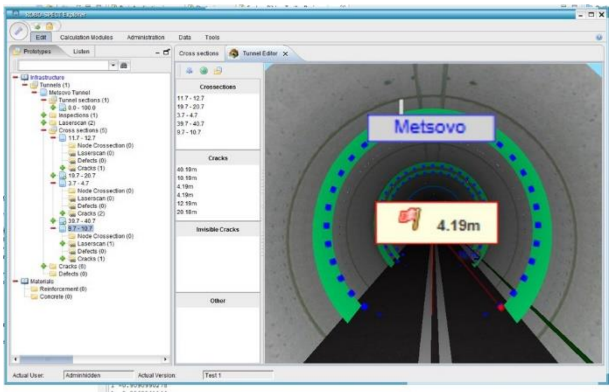

Figure 5. SAT representing the inspection tunnel and processing the data gathered.

4 Safe position of the Ultrasonic Sensors (US) Inspection Tool

This safe positioning process of the US Inspection Tool is composed of 4 steps: arm creates surface map, move tip to a fixed distance from the surface, end-effector trajectory tracking control, and guided US normal approximation and iterative rotation. The general scheme of the algorithm is depicted in Figure 6.

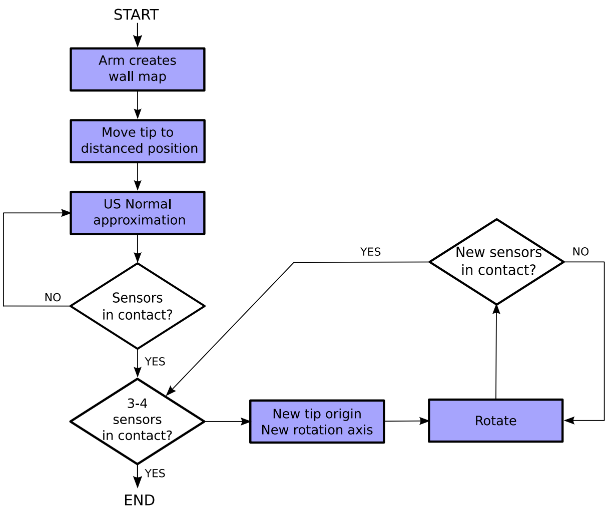

Figure 6. General scheme of the algorithm for positioning of the US Inspection Tool on a crack.

4.1 Arm creates wall map

In order to measure the width and depth of a crack, the arm must place the ultrasonic sensors (US) so that the crack between the acousto-optical ultrasonic detectors, and aligned with the piezoelectric ultrasonic transducers. For the computation of a safe trajectory to the final point, a 2D range robot laser attached to one of the arm's links scans and extracts a 3D point cloud of the surroundings of the crack (Figure 7).

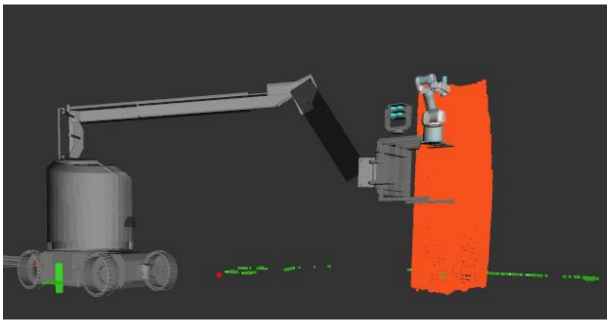

Figure 7. The 3D point cloud scan of the surroundings of the crack is simultaneously simulated.

3D normal to the tunnel linning on the crack position is generated using the extracted 3D point cloud. A safe joint trajectory to position the ultrasonic sensor on the point of the normal at a fixed distance from the crack is then computed [12]. The tracking control algorithm described in Section 4.2 is used to follow the generated trajectory.

The tunnel lining is not a simple flat wall, so the simultaneous contact of the 4 switches is not likely. Therefore, it is suffient to simultaneously contact 3 switches with the surface.

If fewer switches were in contact, the position would not be stable, so the tip would be reorientated by using the information from the contact sensors (Section 4.4). The end-effector control during the approximation and reorientation is described in Section 4.3.

4.2 Move tip to distanced position

The joint space trajectory tracking control used for the arm, it has two feedback loops: the internal motor driver torque controller as inner loop, and the velocity PI controller as an outer loop. The joint velocity v_d command for the outer controller can be described as:

$$v_d = \dot{q}_d + K(q_d - q) \tag{1}$$

where q_d is the joint desired position vector, $\dot{q}_d$ is the time derivative and q is the joint position.

4.3 End-Effector Trajectory Tracking Control

Once the tip has moved to the distanced position, the control scheme used changes. The control scheme used is depicted in Figure 8. It consists of two feedback loops: a kinematic control that generates the joint velocities needed from the desired pose of the end-effector, and the internal joint velocity PI controllers.

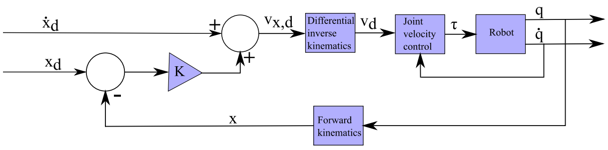

Figure 8. End-effector pose control scheme applied within the reorientation process.

Using the Resolved Motion Rate Control (RMRC) as kinematic control [13], the desired joint velocity vector v_d can be obtained by utilizing the following expression:

$$v_d = \mathrm{J(q)}^{\dagger}(\dot{x}_d + K(x_d - x)) \tag{2}$$

where q is the vector of joint coordinates, $\mathrm{J(q)}^{\dagger}$ is the pseudoinverse of the jacobian matrix, $\dot{x}_d$ is the time derivative of the desired pose vector x_d and x is the pose vector of the end-effector.

4.4 Guided US normal approximation and iterative rotation

The guided approximation and iterative rotation algorithm is based on the iterative change of the tip origin system of coordinates and rotation during the motion described in Section 4.3 around each of its axes until the position is stable (Figure 9). The process depends on which of the switches are in contact:

1. When one switch is in contact, the new origin is placed there and the tip will rotate around one of the frame sides that meet on this corner.
2. In case of two adjacent switches in contact, the new origin is placed in the middle point of the straight line through them, and the tip will rotate around this line.
3. Finally, when two diagonal switches are in contact, the new origin will be the centre of the frame and it will rotate around the diagonal which links them. The algorithm will select clockwise or counter-clockwise rotation in order to obtain more switches in contact.

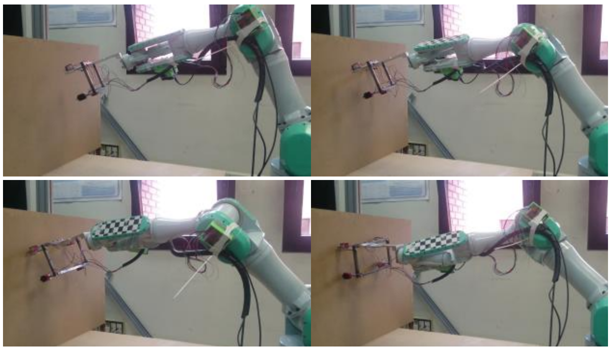

Figure 9. Sequences of the iterative rotation algorithm performed in the laboratory against a flat surface.

5 Laboratory and field experiments and results

The ROBO-SPECT system has been successfully tested in 3 different phases: Simulated environments, laboratory environments, and a roadway tunnel with ongoing traffic.

- In the first phase, the tests were performed within the Gazebo [14] simulator. These experiments served to validate the functionality of the navigation of the mobile vehicle, the trajectory computation and execution of the automated crane, and the US safe positioning US Inspection tool positioning algorithm.
- The second phase of the experiments includes the validation of the different components of the system, and hardware and software integration of the full robotic system also in laboratory settings.
- The full robotic system was tested in Metsovo, Greece, in Egnatia Odos motorway tunnels with ongoing traffic. Field experiments were performed throughout selected validation scenarios, including all the components of the system. These selected mission plans were sent using the Mission Manager with no human intervention and the data gathered during the test was provided to the CR. Roadway tunnel tests covered the capabilities of the system adding complexity. The first scenario consisted on image acquisition every 1.4 m half-slice of the tunnel. The second scenario, added 3D laser profiler scans every 5 m. The third scenario was the same as the second one, but adding crack detection. The fourth scenario included stereo images acquisition and 3D laser profiler scan if a crack is detected. The fifth scenario added the teleoperation mode of the robotic arm to position the US inspection tool on detected cracks to perform width and depth measurements. Finally, the complete robotic inspection procedure was demonstrated in the last scenario, where the safe positioning of US inspection tool on the detected crack is performed autonomously.

6 Results

The complete autonomous inspection was repeated 10 times in a 20 m segment of half of the Egnatia Odos tunnel in order to extracted timing and accuracy data. Table 1 depicts the average time of each inspection process stage gathered from the trials. The total time to inspect one 1.4 m half-slice of the tunnel without cracks (approximately 6 minutes) is highlighted in this Table after the set of stages that are required for this process. In case of a detected crack in a 1.4 m half-slice, it would not take longer than 10 minutes, which is also highlighted after the additionally required stages. The inspected tunnel presents a 2/3 ratio of cracks per half-slice, and the average time to inspect the 20 m tunnel segment was 2 hours and 9 minutes.

The overall error of the ROBO-SPECT system describes the accuraccy of the US Inspetion Tool positioning on a given crack with respect to the global tunnel coordinates. The coordinates ground truth is based on a previously hand-crafted map of tunnel lining cracks. The overall accuracy is shown together with each ROBO-SPECT individual component maximum error in Table 2. For the complete ROBO-SPECT system, the overall maximum error is 11 cm. Fixing the vehicle and crane, it can be seen that a 2.5 cm maximum error of the US positioning with respect to the vision system, which is an admissible error for obtaining US sensor measurements.

Table 1. Inspection process timing of one 1.4 m half-slice.

Inspection process stages	Time [s]
Vehicle motion to next 1.4 m slice	10
Crane motion to first scanning position	21
Crane stabilization	4
Crack detection in 1st position	150
Crane motion to 2nd scanning position	35
Crane stabilization	4
Crack detection in second position	120
Crane go to home position	26
Inspect one half-slice without cracks	**370**
Crane approximate to the wall	7
Robotic arm tip touch the wall	15
US Measurements	80
Laser proler scanning	120
Inspect one half-slice with one crack	**592**

Table 2. Maximum error of the ROBO-SPECT components, and the maximum accumulative error from the chain that begins with the vehicle localization and ends with the US inspection Tool placement.

Individual Component	Maximum Pos. Error [mm]
Vehicle	38
Crane	47
Vision System	16
Robot Laser Sensor	3
Robotic arm	4
US	2

Chain	Maximum Pos. Error [mm]
Vehicle	38
Veh. + Crane	85
Veh. + Crane + Vis.	101
Veh. + Crane + Vis. + Laser	104
Veh. + Crane + Vis. + Laser + Arm	108
Veh. + Crane + Vis. + Laser + Arm + US	**110**

7 Conclusions

ROBO-SPECT is a highly complex robotic system that has demostrotated during the field trials its capability to inspect roadway tunnels autonomously with ongoing traffic on the other line of the roadway, where each component has fullfilled their tasks, p.e, the mobile vehicle has navigated autonomously in a real tunnel using the reflective beacons system and the dedicated laser navigation sensors maintaining a constant parametrized distance to the wall. The automated crane performed trajectory plans with collision avoidance using a 3D point cloud map. The robotic arm process described in this paper in order to place with precision the ultrasonic sensors was positively performed in the tunnel as shown in Figure 10.

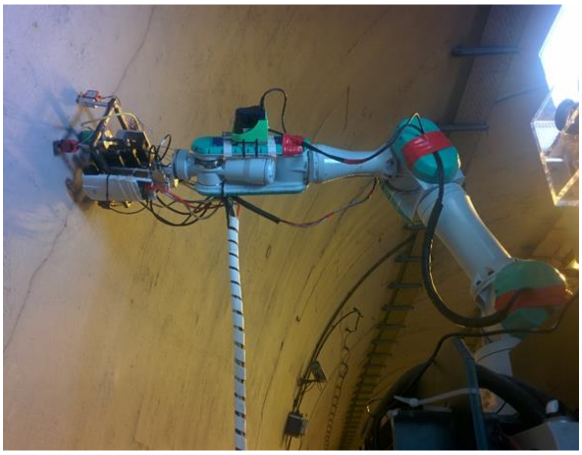

Figure 10. US inspection tool measuring a detected crack in the Egnatia Odos tunnel.

The integrated mode of operation, where the three levels (robotic system, GCS and CR) are connected permanently was tested succesfully gathering data and displaying it in the CR. Hardware and software adaptations allowed the overall system integration in a positive way. The software integration, including IGC and GCS, demostrates that the chosen architecture and protocols perform correctly, including non-standard situations.

The ROBO-SPECT robotic system provides accurate, faster and reliable tunnel lining inspection and assessment with ongoing traffic in safer working conditions.

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