INTEGRATED ROBOTIC SOLUTION FOR TUNNEL STRUCTURAL EVALUATION AND CHARACTERIZATION – ROBO-SPECT EC PROJECT

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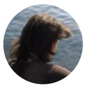

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Integrated Robotic System for Tunnel Structural Assessment - The ROBO-SPECT EC project

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1. Introduction

Tunnel structural inspection is nowadays facing issues involving slow, labour expensive and quite subjective inspections being based on visual (manual) human inspections. Having in mind the increasing safety requirements and needs for higher tunnel uptimes, we can understand the importance of automated inspection and assessment of rail and road tunnels. Recent advances in robotics, computer vision as well as sensorial technologies are today in a quite mature level able to compose automated robotic solutions aiming towards automatic inspection of civil infrastructures and particularly transportation tunnels (road and rail).

ROBO-SPECT is an EC co-funded research project (FP7 - ICT – 611145 - Robotics) that, driven by the tunnel inspection industry, adapts and integrates recent research results in intelligent control in robotics, computer vision and active continuous learning and sensing, in an innovative and integrated, robotic system that automatically scans the intrados of tunnels for potential structural defects on their surface. The robotic system additionally inspects and measures radial deformation in the cross-section, distance between parallel cracks, cracks and open joints that may impact tunnel stability, with mm accuracies. With this integrated technology, the structural condition and safety of tunnels is assessed automatically, reliably and speedily.

This publication focuses on the ROBO-SPECT EC project activities including requirements extraction, specifications and presents the overall system architecture as well as the technologies that will be integrated and overall technological solution towards tunnel structural health monitoring. Also it provides the current status of implementations and following steps as well as its expected European and International impact.

1.1 Tunnel Monitoring Challenges

The tunnelling sector is nowadays facing a series of challenges that current ICT and robotic technologies can significantly aid and support in the upcoming years. Inspection, assessment and maintenance of road and rail tunnels is highlighted under the framework of safe operation of the existing civil infrastructure such as, tunnels, bridges, roads, pipelines, and much more. There are various reasons that have led to the significant and progressive deterioration in civil structures that are in urgent need of inspection, damage assessment and repair. The factors that affect negatively their structural integrity can be: ageing, environmental factors, loading, usage changes as well as inadequate maintenance or deferred repairs. All the above need are more than apparent in underground transportation tunnels including a number of tunnels operating for more than half centuries which already present large evidences of deterioration, whereas there are some collapse paradigms [1, 2, 4].

In summary ROBO-SPECT project will be replying to the following industrial challenges [8]:

- 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 in order 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 categorise them manually – manual, slow and labour expensive process;
- Un-reliable classification of the liner conditions and lack of engineering analysis (following the table below).

2. ROBO-SPECT Project Concept and Objectives

ROBO-SPECT is an EC co-funded research project funded by the European Commission under FP7-ICT (Robotics) that started its operations in October 2013 and is being coordinated by the Institute of Communication and Computer Systems (Athens, Greece).

The objective of ROBO-SPECT is to provide an automated, faster and reliable tunnel inspection and assessment solution that can combine in one pass both inspection and detailed structural assessment that does not or only minimally interfere with tunnel traffic. The proposed robotic system will be evaluated at the research infrastructure of VSH in Switzerland, at London Underground and at the tunnels of Egnatia Motorway in Greece. ROBO-SPECT is expected to:
- Increase the speed and reliability of tunnel inspections
- Provide assessment in addition to inspection
- Minimize use of scarce tunnel inspectors while improve the working conditions of such inspectors
- Decrease inspection and assessment cost
- Increase the safety of passengers
- Decrease the time tunnels are closed for inspection

The technologies that the project will be incorporating towards the above goal are a robotic platform able to operate in tunnels (rail and road) that will be integrated with a suitable robotic arm able to reach the tunnel intrados. The arm will be further equipped with computer vision system and ultrasonic sensors able to detect and classify tunnel surface defects and cracks. A 3D laser scanner will also provide 3D measurements of the defective areas (or areas of interest). The system will be supported by a dynamic decision support system and user interface that will characterise the structural integrity of the tunnel through civil engineering algorithms and thus support the tunnel structural assessment [6, 8].

ROBO-SPECT includes 10 partners carefully selected to form a balanced consortium covering (a) all fields of expertise necessary to handle the objective of an automated, integrated, robotic system for tunnel inspection and assessment in one pass, exploitable in the short to medium term and demonstration of its capabilities to major potential users (b) industrial/commercial involvement to ensure exploitation of the results and (c) the required capabilities in terms of management and dissemination of the results. The ROBO-SPECT partners are being divided into three main categories as follows: End Users (Egnatia Tunnels, VSH Hagerbach Test Gallery, London Underground), Robotic Partners (Universidad Carlos III de Madrid, Robotnik Automation Sll, Cassidian SAS), Inspection partners (Institute of Communication and Computer Systems, Ecole Nationale Des Ponts Et Chaussees, Institute of Microelectronics and Microsystems, Tecniche E Consulenze Nell' Ingegneria Civile, D. Mpairaktaris Kai Synergates-Grafeion Technikon Meleton Etaireia Periorismenis Efthynis, RISA Sicherheitsanalysen Gmbh).

3. The ROBO-SPECT System Modules

The ROBO-SPECT system comprises of the following distinct modules that will be combined into one integrated system serving as the ROBO-SPECT robotic system able to detect anomalies (defects and cracks) on the internal surface of road and rail tunnels. The system components can be summarised to the following modules that are being summarised in the following paragraphs:

- Robotic vehicle with extending arm (boom)
- Computer vision system
- Ultra-sonic sensors
- 3D laser scanning
- Structural assessment software

3.1 Robotic vehicle with boom

The selected robotic vehicle system will comprise of a robotic vehicle able to operate in road and rail tunnels having the relevant capabilities and interfacing (wheels etc). The robotic vehicle is currently being equipped with laser equipment and tag reading capabilities so that it can position and navigate itself into the tunnel environments. The vehicle is electricity powered and this can guarantee its autonomous operation regarding its movement as well as the provision of power to the rest of the sensing/navigation etc equipment on-board. The robotic system itself is also composed by three subsystems: the mobile robot, an automated crane arm (boom) and an industrial-quality robot manipulator. The boom is attached on the robotic vehicle and is responsible for carrying the robotic manipulator closer towards the tunnel internal surface (intrados) to make sure that more precise measurements can be taken. In turn, the robotic manipulator attached at the end of the boom, having a 7degrees of freedom can perform very precise movements so that the suitable sensors can get closer to the tunnel surface and localise themselves on the exact measuring position. Various 1D (laser, infrared and ultrasound proximity and distance sensors), 2D (such as vision camera and LIDAR sensors) and 3D (as in time of flight or similar technology) sensors will be incorporated to the subsystems to improve the behaviour of the system [8].

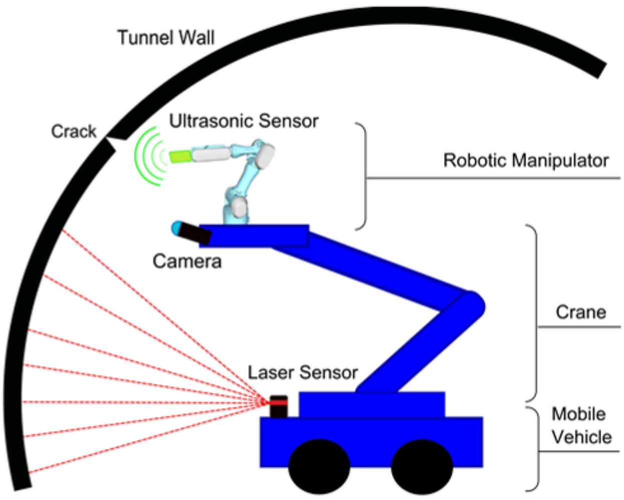

Fig. 1 *ROBO-SPECT System - Concept Diagram*

The design and configuration of the robotic platform has been done having in mind the autonomous-ness, flexibility, operability and manoeuvrability requirements of the system. The work above is being currently developed by the Universidad Carlos III De Madrid (Spain) and Robotnik Automation Sll (Spain).

3.2 Computer vision system

The computer vision system that will be embedded on the robotic manipulator as described above, will be designed, integrated and configured able to perform tunnel structural inspection of the tunnel intrados. Through the vision system, the robotic system will be able to detect structural anomalies (defects) such as cracking, spalling, staining, exposed re-enforcement, white deposits as well as water leakages at the inspected concrete lining intrados. The system will be autonomously collecting 2D images of the tunnel internal surface at a rate of 1m/sec and apply computer vision techniques to detect the relevant surface anomalies. In case of defects detection, the system will stop or slow-down and concentrate the image acquisition on details of interest, thus allowing the higher resolution 3D sampling of these details.

Hierarchical computer vision schemes will be applied so as to make the recognition accuracy just-in-time, and thus significantly reduce the time and effort needed for visual inspections. At the same time the system will extend state-of-the-art vision schemes related to Riemannian Manifolds geometry and constrained optimization methods for the purpose of extracting reliable, robust and precise 3D measurements (with mm accuracy) using either multi-view cameras or even monocular ones.

Learning technologies will be applied to tunnel's inspection in order to achieve on-line understanding of the cracks as the system surveys each tunnel. On top of this, the computer vision systems will be used as the controller for automatically defining the inspection way in terms of speed, orientation and precision of the robotic arm and thus sensing accuracy and level. Recent semi-supervised learning schemes will be applied in the detection of tunnel surface anomalies and thus exploit a small set of labelled data to roughly train some initial classifiers that will be used to detect tunnel defects. The rest un-labeled data will be exploited to re-adjust the classifier based on new knowledge that is currently collected from the robotic/control system. This is crucial for attaining an easy adaptation of the robotic system to different lining types and places, since it is practically impossible to label all the data captured from the tunnels due to time constraints and the huge financial cost required [8]. The relevant work associated with the above technologies is being developed by the Institute of Communication and Computer Systems (Greece) and Ecole Nationale Des Ponts Et Chaussees (France).

3.3 Ultra-sonic sensors

Ultra-sonic sensors are currently being designed and developed through the project activities in order to detect the cracks' width and depth at the tunnels internal side. The cracks will be first located with the computer vision module (see next chapter) and by moving the robotic boom, the system will approach the crack position in order to perform precise measurements of the crack. The ultra-sonic transducers will be combined with optical acoustic, fiber-optic sensors will complement the scattering across the crack with point measurements of the ultrasonic near field scattering [8, 9].

The device under development constitutes of a polymeric, low-finesse Fabry-Perot interferometer manufactured on a silicon micro-machined structure, which is used to mount the detector on the tip of a single mode optical fiber [9]. The principle of operation of the ultrasound detector is based on optical interferometry within the space delimited by the two metal mirrors in the Fabry-Perot cavity, which gives rise to a strong dependence of the overall reflected intensity on the thickness of the polymeric spacer [9].

The two sensing systems will be combined in the integrated system, however preliminarily, better performances I crack depth measurement are expected from the fiber-optic sensors due to the higher sensitivity of the acoustic-optical transducers. On the other hand, the acousto-optical sensors will concurrently be used in crack width measurement according to a new method based on near-field ultrasonic detection close to the crack that is now being exploited [8, 9]. The above described work is being developed by the Institute of Microelectronics and Microsystems (Italy).

3.4 3D Laser scanning

A 3D laser scanner will be used for performing 3D scanning of the tunnel intrados at the points of interest activated by the computer vision system depending on the severity and classification of the defect identified. The 3D laser scanner will be used to create a slice of the tunnel circumference at the selected point (length) of the tunnel. This will measure the distance of every point of its circumference from the (well known) laser (and robotic vehicle) position. This measurement will provide input to the structural assessment tool regarding possible deformations of the tunnel itself. The accuracy of the laser scanner is 0.1mm able to satisfy the high accuracy of the Module on Materials' Degradation in order to provide the Structural Assessment Module with needed time-dependent, quantitative information on geometric and materials' property changes due to materials' deterioration.

The above module will be able to provide direct input to the structural assessment tool including details on the dimensions of the segments along the axis of the tunnel, the perimeter of the cross section of the tunnel as well as the connection patterns between segments characterized by the continuing or alternating location of the horizontal joints between adjacent lateral rings of the tunnel lining. The relevant work associated with the above technologies is being developed by the Institute of Communication and Computer Systems (Greece).

3.5 Structural condition assessment tool

The Structural Condition Assessment Tool is the part of the ROBO-SPECT Project aiming to the preparation of a software for a near real time evaluation of the entities characterizing the structural condition of existing cast in situ or segmental reinforced concrete tunnel linings which is based on data received from measurements of the characteristics of cracks developed on the visible internal face and the deflections of points on it due to its deformation [10].

The tool incorporates two distinct modules that will be combined to get the overall structural condition of the tunnel under inspection. The former is the Local Condition Assessment Module, where the strains, the stresses, the internal forces, the available strength and the safety factors are calculated at the points of the tunnel cross section where cracks have been detected and measured. The latter is the Global Condition Assessment Module where the same entities characterizing the structural behaviour for the totality of the points on the cross section's perimeter are calculated by using the data from the measurements of the deflections at eight points. Additionally, the actual values of the water and soil pressures applied are calculated and possible cracks expected to have developed on the external invisible face of the lining are detected [10].

The above system will also act as the user interface for the tunnel operators and/or inspectors that will use this software to direct the whole robotic inspection process while at the same time be able to extract details on the tunnel condition either on an on-alert or on-demand approach. The user will be able to observe the tunnel position of defects and by clicking to the appropriate tunnel positions will be able to extract and examine the collected information in terms of raw information (images of cracks) or as the results of the system structural assessment. Moreover this tool will generate alerts in case of critical situations and prompt the tunnel operators to examine scenarios for hypothetical situations (e.g., rapid progress of corrosion) while at the same time rapidly repair manageable problems avoiding late-repair costs and the resulting impact on the highway/railway transport system during the the respective repair/reconstructions. This tool is currently being developed by RISA Sicherheitsanalysen Gmbh (Germany), TECNIC - Tecniche E Consulenze Nell' Ingegneria Civile Spa -Consulting Engineers Spa (Italy) and D. Mpairaktaris Kai Synergates-Grafeion Technikon Meleton Etaireia Periorismenis Efthynis (Greece).

4. Expected outcomes and benefits for the Tunnel Society

ROBO-SPECT will be significantly aiding in supporting the tunnel inspection society targeting towards the following main outcomes replying to the following issues [8]:

- 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 in order 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 categorise them manually – manual, slow and labour expensive process.
- Un-reliable classification of the liner conditions and lack of engineering analysis.

Following the integration of the above modules (task of CASSIDIAN SAS as the system integrator), the integrated system is highly expected to bring the following impact to the inspection industry and society in general:

- Permit proactive condition-based maintenance of tunnels,
- Significantly decrease life-cycle maintenance costs per tunnel,
- Increase tunnel safety,
- Eliminate the need for emergency repairs,
- Reduce tunnel closures or partial closures due of tunnel inspections,
- Increase the residual lifetime of existing tunnels,
- Minimise use of scarce tunnel inspectors,
- Improve the working conditions of tunnel inspectors,
- Decrease the engineering time needed to assess the tunnel structural condition,
- Provide better quality, objective, timely data and an improved knowledge of the structural response of tunnels,
- Promote the use of robotics in the civil infrastructure inspection sector and
- Strengthen the global competitiveness of the European tunnel inspection industry

5. Current status of developments and upcoming steps

ROBO-SPECT project has just closed its first year of activities mainly focusing on the extraction of the tunnelling society requirements and challenges. Through extensive consultation with the tunnel operators in the consortium (and the gathered external parties) the project has managed to create a list of requirements that have in-turn been converted into the system technical specifications and system architecture.

Regarding the robotic navigation and intelligent positioning controller preliminary designs of the robotic systems have been also carried out. Computer vision systems and machine learning detection algorithms have started being developed while some major effort has been spent on the organisation and extraction of the visual descriptors and training data gathering. Hundreds of annotated pictures representative of the various types of deterioration in Egnatia Highway, VSH tunnels and London Underground were collected or provided as the first data set for algorithmic training.

Sensor module activities have included the design of the process flow and mask layout for the fabrication of the fiber-optic ultrasound sensors that will be included in the ultrasound sensing system for crack analysis and its preliminary design and testing. Structural engineering activities have focused in the shaping of the Structural Assessment Module and the research and evolution of the underlying theory. Partners have also started working on the deterministic modelling of degradation of the reinforced concrete tunnel lining and the deterministic assessment of the structural condition of the tunnel lining.

The project experimental evaluation is expected to be executed in three stages (experimental tunnels of VSH, actual road tunnels of Egnatia Highway as well as rail tunnels of London Underground) towards the end of the second year of activities. A consolidated benchmarking procedure will be developed inside the project and through this, the whole system evaluation and validation will be executed.

6. Conclusions

This publication has presented the distinct but strongly linked modules of the ROBO-SPECT system providing an overview of each of the developed technologies. The status of developments has also been detailed while some integration steps have also been described. The system is now at its integration stage and further refinements and interfaces development is expected.

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