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Robotic System with Intelligent Vision for Tunnel Structural Assessment - System Architecture – The ROBO-SPECT EC project

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ABSTRACT: Nowadays tunnel structural inspections are executed based on visual (human) inspections. This is a slow process, labour expensive and subjective while requiring lane/rail shutdown during the inspection.

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

This publication focuses on ROBO-SPECT EC project first year activities presenting the overall system architecture as well as the technologies that will be integrated and overall technological solution. The current status of implementations and following steps as well as its expected European and International impact is also included.

1 INTRODUCTION

Structural health monitoring (SHM) can be defined as the diagnosis of the state of a structure and/or of its constituent materials and components or even the structure as a whole system. The parameters that may affect the structural integrity of any structure may range into a series of various parameters including ageing, loading, corrosion etc or even accidental actions. The assessment of structural integrity of existing civil structures is of primal importance in order to identify and determine its reliability levels on the ability to carry existing and future loads and fulfil its task having in mind human life, financial, maintenance and operational risks (Rucker 2006). Civil structure framework, includes functional modules such as buildings, bridges, tunnels or other structures (factories, power plants, heritage structures, ports) and other types such us geotechnical or excavation sites. The inspection and maintenance over such structures depending on the type, performance, safety criticality and ownership, is sometimes imposed by law. The largest challenge over real-time monitoring systems is that all these infrastructures are in general unique. This raises a need for a system able to be adapted to different operational needs and structure types with different monitoring requirements (Aktan, Loupos 2011-2).

- Seismic Event effects on the structure (post and pre);
- Existing structure modifications and external works affecting the structure;
- Structural demolition monitoring or structural materials degradation and fatigue;
- Moving towards performance based design philosophy.

1.1 Structural Health Monitoring Needs and Challenges in Tunnels

Tunnels are very critical type of structures where monitoring proves beneficial towards structural health identification. The SHM of a tunnel is usually focusing on the limits of deformations in terms of structure stability and thus investigating stresses, strains and deflections. Tunneling activity is on the increase around the world while it is not just the volume of work which is raising the demands of modern transport networks but also the facts that tunnels are longer and wider than ever before and are being driven through increasingly difficult ground conditions. Furthermore, there are many tunnels in countries of high seismicity and a good part of them is located in densely populated areas and require very high standards of safety (ASCE 2009). At the same time, there is a worldwide increasing interest on the sensitivity of tunnels to seismic activity. Furthermore damages in tunnel structures are difficult to assess and damaged tunnels that have survived the major earthquake may not have the capacity to survive consecutive seismic aftershocks. After an earthquake, there are critical decisions to be taken from the authorities regarding the shutdown (or not) of the tunnel. A quick and reliable damage detection and assessment of the structure could advice whether the tunnel can remain open or should be shut down. We also observe that seismic activities are not the only reason for the need in obtaining a tunnel structural image. Shut-down of tunnels for extensive repairs can be avoided by having quick, on-time and clear images of the tunnel structural condition, avoiding the resulting impact on the highway or transit system, or investing in very costly reconstruction, also with potential system repercussions (Loupos 2013b, Brownjohn 2015).

2 THE ROBO-SPECT EC PROJECT

ROBO-SPECT is a project co-funded by the European Commission under FP7-ICT (Robotics topic) that started in October 2013 and is 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 interfere with tunnel traffic. The 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 and the system 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

In summary the needs that ROBO-SPECT will be replying to are the following (Loupos 2014):

- 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.

3. ROBO-SPECT Technical Concept

The ROBO-SPECT system comprises of various distinct modules that combine and integrate the full robotic tunnel inspection system. The robotic system modules can be summarised to the following main modules as can be seen in the diagram that follows: Mobile Vehicle, Automated Crane, Robotic Manipulator.

Apart from these main modules, there are various subsystems that operate such as the sensorial systems (including computer vision, 3D laser profiler and ultrasonic sensors), navigation (including laser and landmarking) and communication systems. The above modules are supported by decision support system able to collect the tunnel collected data and perform the relevant processing to examine the tunnel structural condition as well as act as the user interface for the tunnel operators (Loupos 2013, Loupos 2014, Balaguer 2010). A ground control station (GCS) will also support by monitoring constantly the robot mission and being at short distance with the robotic system. A Control room incarnates either the safety control room of the organisation or the system in charge of the infrastructure monitoring along the time. Depending on the accessible communications, the Control Room can or not monitor in real time the robot mission and process the data to update the referential system and compute the tunnel integrity.

The design of the robotic system has been performed having in mind the requirements for autonomous operation into road and rail tunnels, while having input from the involved tunnel operators being able to have congnitive and learning capabilities to ensure identification of tunnel defects in a quick and non-intrusive way. Furthermore the robotic system has been designed with the relevant sensors on board to enable identification of tunnel defects such as cracks, delaminations, staining, spalling, calcium leaching and efflorescence and other.

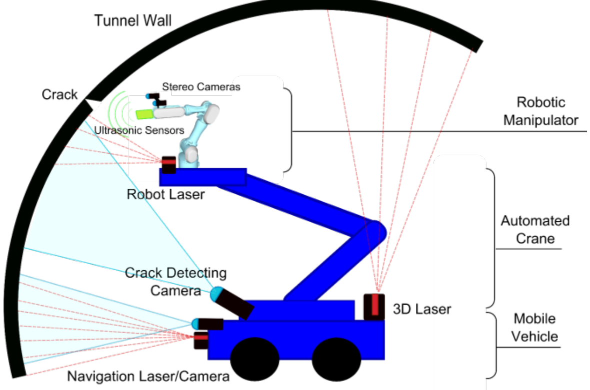

Figure 1: Conceptual design of the ROBO-SPECT system

The mobile vehicle is equipped with crack detection cameras and navigation systems and carries the 3D laser profiler. An automated crane (boom) is placed on the moving vehicle, able to lift the sensors to the proper position around the tunnel surface to perform precise measurements. The sensorial systems in turn, (ultrasonic sensors and stereo cameras) are positioned on the robotic manipulator fixed at the top of the automated crane allowing very precise movements. The tunnel inspection is performed into two ways: The first requires several passes to complete the tunnel inspection but each of the runs will be faster and the tunnel could be used during inspection. In the second option, the inspection of the whole tunnel is accomplished incrementally through small inspection steps, advancing until the whole tunnel is inspected.

4. ROBO-SPECT System Architecture and Design

A bottom down design approach has started from the identification of the three main modules of the overall system these being the control room, the ground control station and the actual robotic system. This has in-turn identified the operational and functional characteristics of each of the components that led to the final system architecture design in operational level.

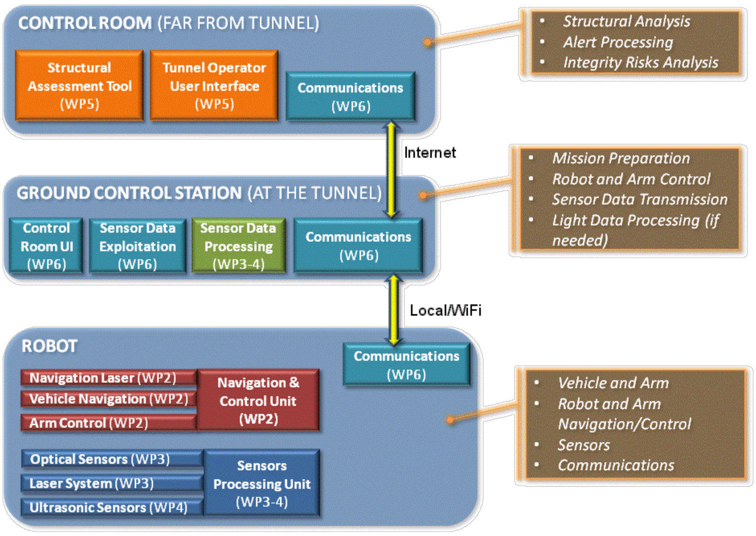

Figure 2: ROBO-SPECT High-level Architecture

The concept of operation, includes the robotic system that consists of the moving vehicle with its navigation systems and arm/boom control and the sensing components (optical sensors, 3D laser system and ultrasonic sensors). The ground control station (at the tunnel level), includes the control room user interface and the sensorial data exploitation and processing and is responsible for the mission preparation, the robot and arm control, the sensor data transmission as well as a light data processing if needed. The control room (located far from the tunnel) includes the structural assessment tool and tunnel operator user interface and is the level where the structural analysis of the tunnel data will be performed and will include tunnel integriry analysis and alerts' processing. The 3 main components of the architecture support a 3-layer processing design which is presented in the figure below.

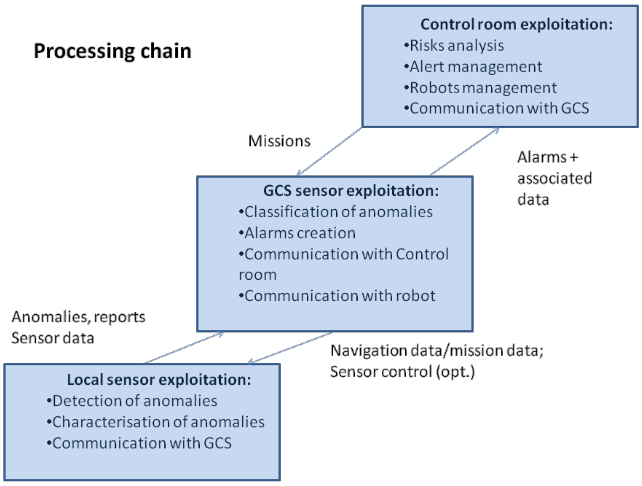

Figure 3: ROBO-SPECT Process design

4.2 Mobile Vehicle System and Boom

The ROBO-SPECT extended mobile robotic system is a wheeled robotic system able to extend an automated crane (boom) to the lengths commonly found in tunnels (up to 11 meters) sustaining a robot manipulator while being automated through the use of robotic controllers. This robotic system is composed by three subsystems: a mobile robot, an automated crane arm, and an industrial-quality robot manipulator (7-degrees of freedom).

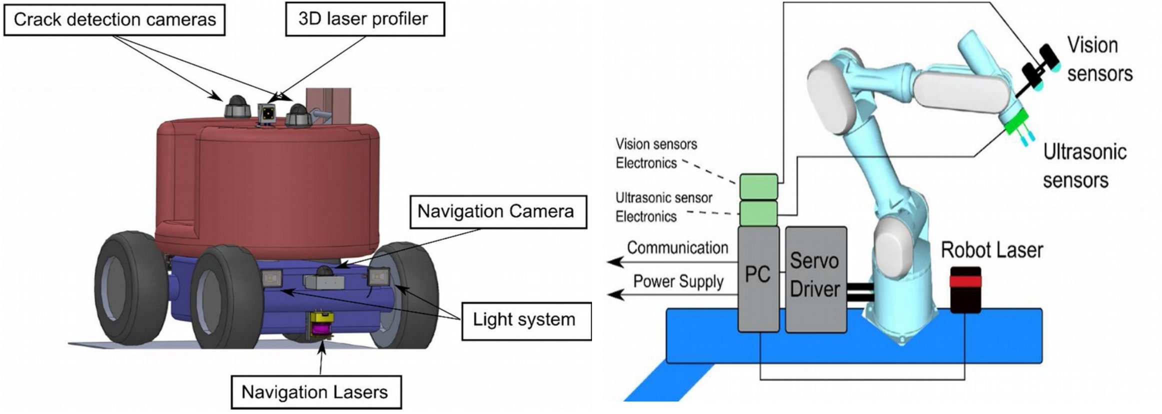

Figure 4: Mobile Vehicle System and Robotic Arm Equipment

Component Based Software Engineering (CBSE) techniques are being developed as a set of low-level device drivers for each of the subsystems (i.e. mobile vehicle, crane and robotic arm) allow for the component's control integration. A system global controller will be developed to improve the position and orientation errors at the end-effector of the robot and to improve the stability of the cameras and ultrasonic sensors. The global controller will have data of three very different natures as inputs: the 3D model data of the tunnel environment coming from the system sensors, as well as semantic information on the state of the system and the required action/behaviour. The intelligent controller updates its prior tunnel model continuously by using the 3D model stream as input .The semantic information will be treated as conditional clauses for generating trajectories that comply with the general system's requisites.

4.3 Computer Vision Sensing

Computer vision (CV) algorithms are being designed to perform tunnel inspection and assessment detecting structural defects (cracking, spalling etc) as well as colour changes (evidence of material deterioration such as corrosion or efflorescence) at the inspected concrete lining intrados. The CV system operates at a rate of about 1 m/sec and acquires 2D images of the tunnel lining at a coarse level of detail applying fast object recognition techniques to identify areas of interest in the coarse 2D image and then, at a slower rate, concentrate the image acquisition on details of interest, thus allowing the higher resolution 3D sampling of these details. Hierarchical computer vision schemes are applied to make the recognition accuracy just-in-time, and thus significantly reduce the time and effort needed for visual inspections. The system will apply recent advances in active continuous learning to tunnels' inspection mechanisms so as to achieve on-line understanding of the cracks as the system surveys the tunnels. The computer vision system additionally acts as the controller to automate the way of inspecting tunnels by modifying the velocity and the orientation of the robotic arm, while incorporates state-of-the-art semi-supervised learning schemes for detecting tunnel anomalies.

4.4 Ultra-Sonic Sensing

The ultrasound-based crack analysis methods that will be developed within ROBO-SPECT take advantage of an innovative ultrasonic detector previously developed by one of the project partners. The device constitutes of a polymeric, low-finesse Fabry-Perot interferometer manufactured on a silicon micromachined structure, which is used to mount the detector on the tip of a single mode optical fiber. The principle of operation of the device as an 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. This effect is exploited for ultrasound detection since when an incoming ultrasonic wave hits the soft polymer spacer, the resulting compression leads to a change of the polymer thickness and consequently to a variation of the reflected optical intensity. By measuring the reflected intensity using a beam splitter and a photodiode at the opposite side of the fiber, the ultrasound signal spectrum can be reconstructed and converted into an electric signal.

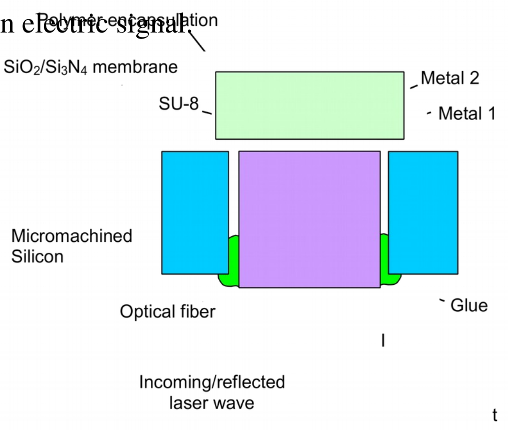

Figure 5: Acousto-optical ultrasound detector by Micro-Opto-Mechanical technology

Thanks to the very high resolution of the optical interferometric readout, the sensor presents a much larger sensitivity than commercially available piezoelectric ultrasound sensors, as demonstrated in recent tests. In ROBO-SPECT, the described acousto-optical ultrasonic detector is used in combination with commercial piezoelectric ultrasonic transducers for crack depth measurements according to the Time of Flight (ToF) measurement method. The acousto-optical sensors will also be used in crack width measurement according to a new method based on near-field ultrasonic detection close to the crack.

4.5 Structural Assessment Software

The structural assessment software is based on input from the inspection by the robotic system, construction information and information on the operative environment, to automatically assess the structural condition and stability of the tunnel at the time of the inspection and at future times so that tunnel managers can decide on an immediate intervention or on the time for the next inspection. Common material defects responsible for the latter degradation in concrete linings produce signs visible at the tunnel intrados (e.g., calcium leaching produces white deposits on the concrete surface and reinforcing steel corrosion produces brown/reddish staining of the surface). Once the computer vision system detects such material defects, quantitative predictive degradation models from the literature, modified to reflect the tunnel conditions, will be used to evaluate the change in the mechanical properties of the lining because of these defects as a function of time in terms of initial conditions (e.g., commissioning year) and identified influential operational parameters (e.g., volume of traffic).Successive inspection results with the computer vision system will be used to assess the rate of attack which will be used to update the above models. The quantitative models described above together with input from inspection on structural damage (e.g., cracks) provide input for the assessment of the stiffness and resistance in lining sections of the tunnel cross-section under study. Accordingly, the following approach will be used for the prediction of future probability of failure as a function of time so that the timing of the next inspection can be determined. The structural assessment at the time of the inspection will determine the ground loads acting on the lining at the time of the inspection. On the assumption that these loads will not change in the future the same approach used to assess the structural condition at the time of the inspection is used for structural analyses for every year of interest, say, 2020, using input in terms of lining properties (derived from the degradation models above) that is appropriate for the year under study.

4.6 Ground Control Station (GCS) and Control Room

The GCS will be designed to monitor constantly the robot mission, a WIFI-type data link is the most appropriate solution. For the link between the GCS and the control room, depending on the distance, the location (indoor/outdoor), the accesses to infrastructure networks and above all the necessity to have a permanent link or not. The solutions can be wireless, access to the nearest access point of the infrastructure network or internet, or a direct connection if the end-user will process the data once back in the company HQ. The Ground Control Station shall be transportable to the tunnel location. The GCS shall be able to operate in an interval of temperatures of 0°C to 30°C. For the tests on the structural assessment module, a demo control room will be used. This demo control room shall encompass: The Control room incarnates either the safety control room of the organisation or the system in charge of the infrastructure monitoring along the time. Depending on the accessible communications, the Control Room can or not monitor in real time the robot mission and process the data to update the referential system and compute the tunnel integrity.

3 CONCLUSIONS

ROBO-SPECT project is now at the integration phase where all system components are being integrated into a complete solution and the system 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) now. A consolidated benchmarking procedure will be developed inside the project and through this, the whole system evaluation and validation will be executed.

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