Robotic Intelligent Vision and Control for Tunnel Inspection and Evaluation - The ROBINSPECT EC Project

Konstantinos Loupos
Institute of Communication and Computer Systems
Athens, Greece
kloupos@iccs.gr

Angelos Amditis
Institute of Communication and Computer Systems
Athens, Greece

Christos Stentoumis
Institute of Communication and Computer Systems
Athens, Greece

Philippe Chrobocinski
CASSIDIAN SAS
Elancourt, France

Juan Victores
Universidad Carlos III De Madrid
Madrid, Spain

Max Wietek
VSH Hagerbach Test Gallery Ltd
Flums, Switzerland

Panagiotis Panetsos
EGNATIA Odos AE
Thessaloniki, Greece

Alberto Roncaglia
Institute of Microelectronics and Microsystems,
Bologna, Italy

Stephanos Camarinopoulos
RISA Sicherheitsanalysen Gmbh
Berlin, Germany

Vassilis Kalidromitis
TECNIC - Tecniche E Consulenze Nell' Ingegneria Civile Spa -Consulting Engineers Spa
Rome, Italy

Dimitris Bairaktaris
D. Mpairaktaris Kai Synergates-Grafeion Technikon Meleton Etaireia Periorismenis Efthynis
Athens, Greece

Nikos Komodakis
Ecole Nationale Des Ponts Et Chaussees
Marne La Vallee Cedex 2, France

Rafa Lopez
Robotnik Automation Sll
Valencia, Spain

Abstract — Recent developments in robotics and the associated fields of computer vision and sensors pave the floor for automated robotic solutions, exploitable in the wider field of inspection of civil infrastructures and particularly transportation tunnels, the latter ageing urgently requiring inspection and assessment. Currently, tunnel inspections are performed via visually by human operators. This can result into slow, labour expensive and subjective process often requiring lane shutdown during the inspection, parameters that need to be lowered while having safety requirements and tunnel uptimes increasing.

ROBINSPECT is an EC research project (FP7 - ICT – 611145) driven by the tunnel inspection industry, that adapts and integrates recent research results in intelligent control in robotics, computer vision and active continuous learning and sensing, in an innovative, integrated, robotic system that automatically scans the intrados of tunnels for potential defects on the surface while at the same time inspects and measures radial deformation in the cross-section, distance between parallel cracks, cracks and open joints that impact tunnel stability, with mm accuracies. Intelligent control systems and robotics are integrated to set an automatic robotic arm manipulation and autonomous vehicle navigation so as to minimize humans' interaction during tunnel inspection. This way, the structural condition and safety of a tunnel is assessed automatically, reliably and speedily. The robotic system will be evaluated at the research infrastructure of tunnels of VSH, at three road tunnels of the Egnatia Motorway and the rail tunnel of London Underground.

This paper will focus on the ROBISPECT EC project first year activities starting from the requirements, specifications and system architecture as well as the technologies that will be integrated and overall technological solution. Also it will provide the current status of implementations and following steps as well as its expected European and International impact.

Keywords— robotics, structural health monitoring, tunnel inspection

I. INTRODUCTION

Recent research in the robotics sector and the relevant sectors such as computer vision and sensors, have significantly increased the competitiveness of components needed in automated systems that can perform one-pass tunnels' (or in general transportation and tunnel infrastructures') inspection and assessment. However, such an integrated and automated system is highly missing today. The work that will be presented in this publication, offers an automated system integrating all the required components for the inspection and assessment of tunnels in one pass.

A. *Tunnel Inspection Requirements*

Following the concept of ROBINSPECT, there are a series of challenges that engineers are facing. The greatest challenge is the inspection, assessment, maintenance and safe operation of the existing civil infrastructure such as, tunnels, bridges, roads, pipelines, and much more [1]. Nowadays, civil infrastructures are progressively deteriorating and are in urgent need of inspection, damage assessment and repair due to ageing, environmental factors, loading, usage changes as well as inadequate maintenance or deferred repairs. The above needs 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 [2].

In summary the needs that ROBINSPECT will be replying to 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 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).*

TABLE I. CLASSIFICATION OF CRACKING AND SPALLING DEFECTS IN CONCRETE LININGS [3]

Defect Type	Minor	Moderate	Severe
Cracking	Up to 0.8 mm wide	From 0.8 mm to 3.2 mm wide	Over 3.2 mm wide
Spalling	75 mm to 150 mm in diameter	~ 150 mm in diameter	More than 150 mm in diameter

B. *ROBINSPECT Concept*

ROBINSPECT is a project co-funded by the European Commission under FP7-ICT (Robotics topic) that launched its activities in October 2013 and is being coordinated by the Institute of Communication and Computer Systems (Athens, Greece). The main objective of ROBINSPECT 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. ROBINSPECT 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*

ROBINSPECT project 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 ROBINSPECT 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).

II. ROBINSPECT TECHNOLOGIES

A. *Robotic Systems for Tunnel Inspection*

The ROBINSPECT extended mobile robotic system will be a wheeled robotic system that will be able to extend an automated crane to the lengths commonly found in tunnels (4 to 7 meter range) sustaining a robot manipulator while being automated through the use of robotic controllers. This robotic system will be composed by three subsystems: a mobile robot, an automated crane arm, and an industrial-quality robot manipulator. The manipulator will be a 7 degrees of freedom robot able to follow the required trajectories while avoiding possible obstacles. The extra degree of freedom ensures the positioning of the sensors attached in a variety of orientations.

Basic 1D (such as 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. Apart from that, a special new ultrasonic sensor to measure cracks width and depth will be attached to the tip of the robot. Figure 1 shows a schematic view of the system. Note this is an early stage of the project and the final system may be different than shown here.

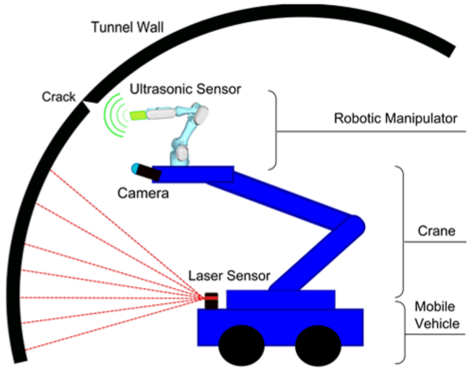

Fig. 1. Conceptual design of the ROBINSPECT system

To ensure one-pass inspection and assessment, the inspection process will comprise a three-step approach involving a coarse inspection phase to provide a general vision of the tunnel to be inspected; a visual inspection in regions of interest and a fine precision inspection procedure to measure the characteristics of the crack being examined. The different inspection steps will generate different behaviours and trajectories controlled by the software drivers. The process will begin creating a general 3D model of the relevant tunnel segment. The inspection trajectory will be generated using that 3D model and the robot will follow it while taking images with the camera system. The more precise inspection stages are executed when needed as a subroutine, so the robot can stop the general trajectory, follow a new path to inspect the crack, and return to the previous process after that.

At software level, Component Based Software Engineering (CBSE) techniques will be applied. A set of low-level device drivers for each of the subsystems (i.e. mobile vehicle, crane and robotic arm) will be developed to allow the component's control to be integrated into the developments of the following tasks of the project. Currently, several robotic software architectures (YARP, ROS, OROCOS, etc.) for implementing CBSE exist and are interoperable. The dynamic and kinematic requirements of the robotic platform needed to reach the measurement area will be designed. Special attention will be placed in keeping the vehicle stability as well as developing the platform modular enough to allow both road and railway navigation. Controllability will be improved as much as possible to achieve an accurate path following in tunnels.

A global controller for the system will be developed in order 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. Furthermore, the three different subsystems (the mobile robot, the automated crane arm, and the robot manipulator) must fulfil a set of required behaviours conjunctly and only a global controller can assure coherent and optimized trajectories. The input of this global controller will include data of three very different natures: an online stream of updated 3D model data of the tunnel environment coming from the 1D/2D/3D sensors, associated uncertainties (both intrinsic to the nature of the sensors and information regarding the confidence at each given instant), and additional semantic information regarding the state of the system and the required action/behaviour.

An intelligent controller will be developed as the global controller. It will update its prior belief model of the environment continuously by using the 3D model stream as input while taking into account the uncertainties as confidence values of the given data. The semantic information will be treated as conditional clauses for generating trajectories that comply with the general system's requisites. The feedback will be used for the global controller to auto-tune its parameters. The system's safety for the robotic system and environment will additionally be assured by the local controllers developed for each of the subsystems as the global intelligent controller is set at the high level to send references to these (and not directly on the actuators).

B. Vision-based systems for Tunnel Inspection

The computer vision system of ROBINSPECT, will be designed and integrated for tunnel inspection and assessment of the structural condition that will detect structural defects (e.g., cracking, spalling) and colour changes (evidence of material deterioration such as corrosion or efflorescence) at the inspected concrete lining intrados. This system, at a fast rate of about 1 m/sec, will acquire 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 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 (in millimeter accuracy) using either multi-view cameras or even monocular ones. 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 will additionally act as the controller to automate the way of inspecting tunnels by modifying the velocity and the orientation of the robotic arm. The computer vision system of ROBINSPECT will also incorporate recent state-of-the-art semi-supervised learning schemes towards detecting tunnel anomalies. Semi supervision will exploit a small set of labeled data to roughly train some initial classifiers that will be used to detect tunnel defects. Then, the abundant amount of unlabeled 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.

Fig. 2. : Computer Vision Cameras - Lab apparatus

C. *Ultrasonic, Crack Width and Depth Measurement Sensors*

The ultrasound-based crack analysis methods that will be developed within ROBINSPECT will take advantage of an innovative ultrasonic detector previously developed by one of the project partners (CNR) [4]. A schematic representation of this device is reported in Fig. 3.

The device is constituted by 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 (schematically represented by the intensity/thickness plot in the figure).

This effect can be 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.

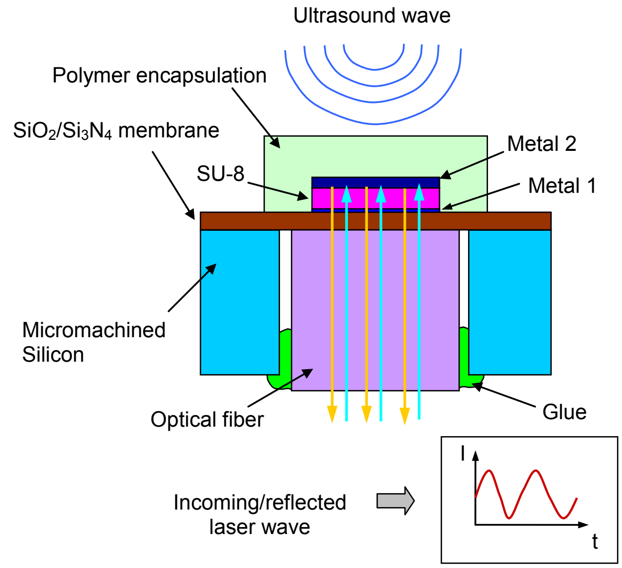

Fig. 3: Acousto-optical ultrasound detector by Micro-Opto-Mechanical technology.

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. For employment in ROBINSPECT, the described acousto-optical ultrasonic detector will be used in combination with commercial piezoelectric ultrasonic transducers as shown in Fig. 4 for crack depth measurements according to the Time of Flight (ToF) measurement method recently proposed in [5], which represents an improvement of the one originally described in the well-known British standard on the measurement of ultrasonic pulse velocity in concrete [6], [7].

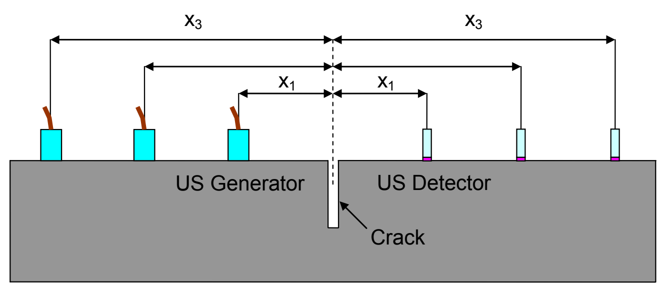

Fig. 4: Crack depth measurement on concrete based on ToF analysis.

From the use of the fiber-optic acoustic detectors in this setup, better performances in crack depth measurement accuracy are expected thanks to the higher sensitivity of the acousto-optical transducers, which may allow for use of higher ultrasound frequencies in the ToF analysis and consequently lead to higher spatial resolution in scattering analysis using shorter wavelengths. 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.

D. *Tunnel Structural Assessment Software*

The aim of this software is, based on input from the inspection with 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.

There can be a degradation of the lining as a function of time. 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) will provide input for the assessment of the stiffness and resistance in lining sections of the tunnel cross-section under study. It will be used in quantitative, mechanical models that will be developed to assess the structural condition and safety of the tunnel lining at the time of the inspection based on measurements of the deformed shape of the tunnel cross section provided by the inspection.

Lining deterioration as a function of time will cause the risk of structural failure to accelerate. 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 (at least until the next inspection), the same approach used to assess the structural condition at the time of the inspection will be used to perform 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.

The assumption that the loads on the lining are constant is valid for the overwhelming majority of tunnels that are more than 20 years old (at which point the temporary support has failed completely and all loads are being carried by the final lining) and there is no new adjacent underground construction.

III. ROBINSPECT EXPECTED IMPACT

A. *Impact to Society*

Today's tunnel environment can be characterized by high user demand, stretched budgets, declining staff resources, and tunnel infrastructures showing signs of age. As there is extensive deterioration in many tunnel cross sections deferred or neglected, repair can potentially exacerbate their condition. If a tunnel is not properly preserved through timely repair of manageable problems, the tunnel owner will eventually has to choose from two very undesirable options: shut down the tunnel, accepting the resulting impact on the highway, railway or rapid transit system, or invest in very costly reconstruction, also with potential system repercussions during the period of reconstruction. Robotic automation can play an important role in providing an answer to the major societal challenge of inspecting and assessing the ageing infrastructure.

ROBINSPECT project will contribute to the above societal issues through a series of research activities such as:

- Permit proactive condition-based maintenance of tunnels by inducing 'Corrective/Reactive Maintenance' approaches allowing optimization of the timing of inspections (and thus, optimization of the repair intervals) based on the probability of failure instead of the current schedule-based maintenance. This will allow maintenance to be performed prior to significant structural deterioration. This is expected to highly increase tunnel safety while decrease life-cycle maintenance costs.
- Reduce tunnel closures or partial closures for inspections. The impact of this will be significant for tunnels with heavy traffic volume. There are traffic jams in some such tunnels even without tunnel partial closures: For the Tauern tunnel for example, traffic jams of 100 km are not considered exceptional anymore.
- Minimize use of scarce tunnel inspectors. Presently, tunnel structural maintenance is largely based on biannual visual inspections [3], [8], [9], [10]. Such inspections are labor intensive and subjective. The proposed automated system will provide objective results and minimize the need for human inspectors.
- Provide better quality, objective, timely data and an improved knowledge of the structural response to ambient disturbances of in-service tunnels over their lifespan. This will have an influence on the initial design phase as well making possible to avoid unnecessarily conservative stress analysis procedures.
- Promote the use of robotics in civil infrastructure inspections while increasing the competitiveness of the European robotics industry through new high added value products. This is also expected to strengthen the global competitiveness of the EU tunnel inspection industry.

B. *European Added Value*

Inspection and assessment of existing tunnels can cause severe traffic disruption and increased costs in ALL European countries at a time of major Europe-wide problems of traffic congestion and the associated pollution on the transit routes and the cities [11]. Things are going to get worse in the future: According to ERTRAC 2010 [12], transport demand in EU is set to grow by 50% over the coming two decades while the rate of expansion of the transport infrastructure will not keep pace with the above increase in demand. To rise to this challenge innovative solutions for inspection and assessment of the transportation infrastructure in order to increase the uptime have to be supported in a coordinated fashion at the EU level.

ROBINSPECT is in line with ERTRAC Strategic Research Agenda (SRA) (2010) [12] that recommends EC funding of research on management concepts, procedures and practices to ensure that infrastructural uptime remains at optimal levels; in line with ERRAC SRA (2007) [13] that recommends EC funding of research on more automated inspection of the rail transport infrastructure; in line with ECTP Focus Area Underground Construction (FAUC) SRA (2005) [14] that recommends EC funding of research on robotized vehicles for service and maintenance of tunnels; in line with ECTP Focus Area Networks SRA (2005) [10] that recommends EC funding for the development of automated non-destructive inspection techniques for reliable assessment of structural elements to minimize the impact on traffic; in line with EUROP SRA [15] that recommends the creation of new robot markets robots through technology transfer and includes robots for inspection in these and in line with the Lisbon strategy to shift resource-intensive activities to a knowledge-based economy.

The EU market as well as the world market is being targeted for the project results. It is thus useful to have reputable partners from seven European countries several of which are active in numerous European countries and abroad. It is expected that new markets for robotics will grow rapidly and inspection of the tunnel infrastructure and civil infrastructure are such new, large markets. It is important that European companies lead these markets.

ROBINSPECT will provide much needed data on the demand placed on tunnels under operating conditions throughout their lifetime. These data will be immediately usable throughout the Union. With this knowledge better EU standards for the design and inspection of tunnels will be executed.

IV. ROBINSPECT Project Status and Next Activities

ROBINSPECT is now approaching the completion of its 1st year activities that have mainly focused on the formation of a user group while at the same time prepare and execute the methodology to extract the end-user requirements. Works focused on the analysis of the end-user requirements, a work that is expected to conclude and result into the Final System Specifications and 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. Further 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. Closing 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.

V. Disclaimer

The ROBINSPECT EC Project (FP7) will be subject to an acronym change and is in no way related to the commercial product “Robinspect"

VI. References

[1] ASCE – American Society of Civil Engineers (2009). ‘2009 Report Card for American Infrastructure,’ (online).

[2] Balaguer, C; Victores, J. G. Technology Innovation in Underground Construction. Chapter: Robotic tunnel inspection and repair. pp.445-460. ISBN: 9780415551052. CRC Press. 2010.

[3] Federal Highway Administration (FHWA), Federal Transit Administration (FRA). (2005). Highway and Rail Transit Tunnel Inspection Manual, US Department of Transportation (DOT), Washington, DC.

[4] L. Belsito, F. Mancarella, M. Ferri, A. Roncaglia, E. Biagi, S. Cerbai, L. Masotti, G. Masetti, N. Speciale, “Micro-Opto-Mechanical technology for the fabrication of highly miniaturized fiber-optic ultrasonic detectors”, Tech. Digest of Transducers 2011, Page(s): 594 – 597, 2011.

[5] R. C. A. Pinto, A. Medeiros, I. J. Padaratz, P. B. Andrade, “Use of Ultrasound to Estimate Depth of Surface Opening Cracks in Concrete Structures”, http://www.ndt.net/?id=9954, 2010.

[6] BS 1881: Part 203, “Recommendations for measurement of the velocity of ultrasonic pulses in concrete”, London, 1986.

[7] J. H. Bungey, S. G. Millard, M. G. Grantham, Testing of concrete in structures, 4 ed. Taylor & Francis, 2006.

[8] European Commission, COM (2007) 551 Final, Green Paper. Towards a New Culture for Urban Mobility, Brussels, 25/9/2007.

[9] European Construction Technology Platform (ECTP) Focus Area Networks. (2005). ‘Networking Europe: Vision 2030 and Strategic Research Agenda,’ Oct. 19, 2005 (12/3/2012).

[10] European Construction Technology Platform (ECTP) Focus Area Underground Construction (FAUC). (2005).’Strategic Research Agenda 2020,’ Oct. 2005 (12/3/2012).

[11] ROBINSPECT Project ” Description of Work”.

[12] European Road Transport Research Advisory Council (ERTRAC). (2010). ‘Strategic Research Agenda 2010. Towards a 50% more Efficient Road Transport System by 2030’.

[13] European Rail Research Advisory Councel (ERRAC). (2007). ‘Strategic Research Agenda 2020, (12/3/2012).

[14] European Construction Technology Platform (ECTP) Focus Area Underground Construction (FAUC). (2005).’Strategic Research Agenda 2020,’ Oct. 2005 (12/3/2012).

[15] European Robotics Technology Platform (EUROP). (2009). ‘Robotic Visions to 2020 and Beyond’ (12/12/2012).