Past, Present and Future of Robotic Tunnel Inspection

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Abstract –

Nowadays, the vast majority of the tunnel inspection processes are performed manually by qualified operators. The process is subjective and the operators need to face very uncomfortable and even dangerous conditions such as dust environments, absence of light, or toxic substance exposition among others. Robotic technology can overcome many of these disadvantages and provide quality inspections collecting different types of data. This paper presents the key aspects of tunnel inspection and a survey of the developed robotic tunnel inspection systems up to date. Additionally, two projects regarding automation of the processes involved and future trends will be discussed.

Keywords -

Robotics, Automation, Inspection, Maintenance, Tunnels, IAARC

1 Introduction

One of the greatest challenges engineers face is the inspection, assessment, maintenance and safe operation of the existing civil infrastructure. This includes large-scale constructs such as tunnels, bridges, roads and pipelines. In the case of tunnels (water supply, metro, railway, road, etc.), they have increased in both total length and number, and will continue to do so. Furthermore, some tunnels still in service were completed over 50 years ago, with the existing construction and materials technology.

Only in Japan in 2006, the number of active tunnels was up to 9000 [1], with tunnels such as the Seikan Tunnel, which is 54 km long and partially below the seabed [2]. Figure 1 shows the evolution of Japanese tunnels in terms of number and length until 2006.

Tunnels progressively deteriorate due to ageing, environmental factors, increased loading, change in use, damages caused by human/natural factors, inadequate or poor maintenance, and deferred repairs. Unfortunately, several incidents related to the structural condition of tunnels have taken place, such as the Big Dig ceiling collapse in 2006 in Boston [3], or the Sasago Tunnel collapse in 2012 in Tokyo [4].

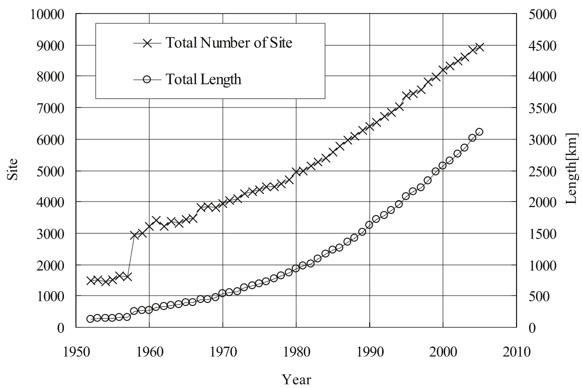

Figure 1. Changes in the number and total length of road tunnels in Japan (2006) [1]

These examples highlight the need of automated, cost-effective and exhaustive inspection of tunnels that prevents such disasters. In this work, we present current tendencies and future trends within this area.

This paper will describe the key aspects of the tunnel inspection procedures and the main advances in robotic tunnel inspection technology. Section 1 defines the main tunnel defects to identify and the principal methods to detect them. Section 2 describes the motivations to use robots in this task and includes a review of the robotic tunnel inspection systems developed up to date, while Section 3 describes the main drawbacks of these systems. In section 4, two relevant European projects regarding automatic tunnel inspection systems are discussed. Section 5 focuses on the future trends that can be applied to the robotic tunnel inspection area. Finally, the conclusions of the paper are included in Section 6.

1.1 Tunnel Defects

The first aspect of inspection that must be defined is the related to the types of defects that may affect tunnels. Identifying these defects is crucial for performing a successful inspection, verifying the state of a tunnel, and performing maintenance if required.

The following list of common defects in tunnels is based upon the *TOMIE Manual* [5], created by the Federal Highway Administration (FHWA).

- Concrete structures: scaling, cracking (traverse, longitudinal, horizontal, vertical, diagonal, pattern, d-cracks, random), spalling, joint spall, pop-outs, efflorescence, staining, delamination, honey-comb, leakage

- Steel structures: corrosion, cracks, buckles and kinks, leakage, protective layer fail

- Masonry structures: masonry units (displaced, cracked, broken, crushed, or missing), mortar, shape, alignment, leakage

- Timber structures: decay, insects, checks/splits, fire damage, hollow area, leakage

The walls of most tunnels are made of concrete, though these walls may contain finishes such as ceramic tiles or metal panels. In most cases, the typical defects found in a tunnel are cracks, spalling and efflorescence/leakage [6]. Examples of this type of defects are displayed in Figure 2. If the walls are covered by a finish, the condition of such walls is generally defined by the deficiencies of the finish on the wall surface. An analysis of the causes of these common defects in tunnels can be found in the work by C. C. Xia et al. [7].

1.2 Tunnel Inspection Methods

The purpose of inspection is to check if a structure that has been functional for years is still safe or not. Furthermore, it is desirable to do this without creating any negative effect on the structure or component, and this is why the non-destructive inspection (NDI) methods [5][8] are far more commonly used than destructive methods. As said before, the most common structural material in tunnels is concrete, thus the following inspection processes are usually applied to concrete tunnels. NDI methods in structures can be divided in visual, strength-based, sonic and ultrasonic, magnetic, electrical, thermography, radar, radiography, and endoscopy methods.

Figure 2. Examples of spalling (left) and crack with efflorescence (right) [5]

1.2.1 Visual Methods

Visual testing is probably the most important of all non-destructive tests. It can often provide valuable information to the well-trained eye. Visual features may be related to workmanship, structural serviceability, and material deterioration, and it is particularly important for the engineer to be able to differentiate between the various signs of distress that may be encountered. Information can be gathered from visual inspection to give a preliminary indication of the condition of a structure and allow the formulation of a subsequent testing program.

1.2.2 Strength Based Methods

Rebound and penetration tests measure the surface hardness of materials and provides an estimation of surface compressive strength, uniformity and quality of the structure. Examples include the Schmidt Hammer [8][9] (rebound), the Windsor Probe [8][10] (penetrating), Flat Jack Testing [11][12] (applied to masonry), or methods without contact [13].

1.2.3 Sonic and Ultrasonic Methods

In sonic methods, also known as impact-echo tests, hammer blows create impulses, and the time of travel of these sonic pulses is measured with pickups placed on the wall [14][15][16], as can be seen in Figure 3. The time of travel is related to the modulus of elasticity and, hence, the strength. Sometimes chain drags, sounding rods or standard hammers are used for detecting delamination on horizontal surfaces if the inspector has experience in detecting hollow sounds.

Figure 3. Inspection using an impact hammer [17]

Ultrasonic devices are normally used by measuring the velocity in the material of a pulse generated by a piezoelectric transducer [18][19][20]. The pulse velocity depends on the composition and maturity of the structural material and its elastic properties. The relationship to strength depends on several other properties and is best determined experimentally [21].

1.2.4 Magnetic Methods

Magnetic methods are used to determine the position of reinforcements and are not techniques for detecting defects or deterioration directly, but the fact that inadequate cover is often associated with corrosion-induced deterioration indicates that a method for locating the reinforcing bars can be important in corrosion control. Examples of these methods are the Magnetic Flux Leakage method [22][23] or the Magnetic Field Disturbance method [5].

1.2.5 Electrical Methods

Electrical methods for inspection of tunnel components include resistance and potential measurements [24][25][26][27]. Electrical resistance has been used for measuring the permeability of deck seal coats and involves measuring the resistance between the reinforcing steel and surface, while electrical potential differences are caused by corrosion of reinforcement.

1.2.6 Thermography Methods

Infrared thermography measures the thermal radiation emitted by the tunnel's walls. Infrared registration techniques allow visual presentation of the temperature distribution on the surface [28][29][30].

The temperature on the surface represents the thermal flow through the surface, which in turn is influenced by the mechanical and/or hydraulic discontinuities of the structure. Consequently, thermal discontinuities on a surface reflects abnormalities within the underlying structure.

1.2.7 Radar Methods

Radar methods have been widely used to detect defects in tunnels and other structures, and the most used is the Ground-Penetrating Radar (GPR) [31][32][33][34]. GPR is the electromagnetic analogue of sonic and ultrasonic pulse echo methods. It is based on the propagation of electromagnetic energy through materials of different dielectric constants. The greater the difference between dielectric constants at an interface between two materials, the greater the amount of electromagnetic energy reflected at the interface.

1.2.8 Radiography Methods

X-rays, gamma radiation or neutron rays can penetrate structural materials and therefore can be used on inspection purposes [35][36][37]. The amount of radiation absorbed by the material is dependent upon the density and thickness. This radiation can be detected and recorded on either film or sensitized paper, viewed on a fluorescent screen, such as a television screen, or detected and monitored by electronic sensing equipment. Using this method, limitations are imposed by accessibility to both sides of the object, long exposure times, and safety precautions required to protect both the operators and public.

1.2.9 Endoscopy Methods

Endoscopes or videoscopes consist of rigid or flexible viewing tubes that can be inserted into pre-drilled boreholes of an element under investigation to examine its condition [38][39]. Light can be provided by glass fibers from an external source. In the rigid tubes, viewing is provided through reflecting prisms and, in the flexible tubes, a fiber optics system is used. New models consist of an additional CCD chip to improve the images. These scopes allow close examination of parts of the structure that could not be otherwise viewed. Although this is a viewing instrument, some minor destruction of material is necessary for its proper use.

2 A Survey on Robotic Inspection

Even with the great variety of inspection methods presented in Section 1, presently structural tunnel inspection is predominantly performed through scheduled, periodic, tunnel-wide visual observations by inspectors who identify structural defects and rate these defects. This process is slow, labor intensive and subjective (depending on the experience and fatigue of the inspector), working in an unpleasant environment due to dust, absence of natural light, uncomfortable conditions or even toxic substances such as lead and asbestos. These working conditions are a main motivation behind the development of robotic systems.

2.1 Robotic Tunnel Inspection Systems

The use of robotics systems in the construction field had been a common research area, and several studies review the advantages in the use of robotic platforms for construction [40][41] and underground construction [42] purposes. Robotic systems can complete the inspection process with objective results and high efficiency. They also improve safety by performing inspection in dangerous environments instead of the inspectors.

Therefore, manual and (human) visual inspection are being replaced with more precise methods using mechanical, electronic and robotic systems and processing data provided by cameras, laser, sonar, etc. The following review will cover a variety of robotic systems using different kinds of sensors to detect defects on tunnels. Each subsection describes a different approach to inspect the tunnel.

2.1.1 Visual Methods

In the case of the system in the Figure 4, a small mobile robot is equipped with a CCD camera [43][44][45]. The robot stays at a constant distance of the wall using a differential-drive wheel configuration, and a set of photos are taken. The camera is mounted on an anti-vibration device to stabilize the images. The robot goes through all the tunnel performing the inspection, but the data is processed after all the images are collected. The inspection consists in the detection of cracks via computer vision algorithms.

A similar robot can be found in the work by F. Yao et al. [46][47]. In this case, the mobile robot is equipped with 21 ultrasonic sensors and 6 video cameras. These sensors are mounted on the same plane and with a semi-ring shape. The inspection consists in the scan of the tunnel lining to search for deformations. The experimental results show that this system can detect the deformed inner-walls at the division of 14 mm when the robot moves at 20 mm/s.

Figure 4. Robotic platform with camera used in tunnel inspections [43]

2.1.2 Impact Methods

Figure 5 shows a system built with an industrial manipulator robot [48]. The system consists of an eight-ton truck used as a base machine, tunnel cross section measuring systems, Electronic Distance Measuring (EDM) instruments employed to measure impact locations, an impact unit with five hammers that generates impact sounds and its equipped on the robotic arm, a lifter that raises the robot up to ceiling level, and finally a computer unit that controls all these components.

Figure 5. A robotic tunnel inspection system that uses the impact sound method [48]

The system uses an impact acoustics method for the inspection procedure, which impacts the concrete wall with hydraulic hammers, converts the impact sounds into electric signals, and then analyses them. The system is capable of finding exfoliation and cavities in a concrete lining. In order to maintain stable attitude, the truck has been equipped with outriggers on the non-motorized wheels. Three people conduct the impact sound diagnosis: a supervisor, an operator and a driver. The machine is operated from the touch panel of the computer that is situated at the operator console.

Another example, seen in Figure 6, uses two lasers to perform a hammer-like inspection to detect inner defects in concrete structures like transportation tunnels [49]. The system is mounted on a motor vehicle and the technique is based on the initiation and detection of standing Lamb waves (or natural vibration) in the concrete layer between surface and inner defects. The concept consists in one laser used like a hammer to impact the surface and another one used to take the measurements. The system can detect various types of inner defects like voids, cracks and honeycombs. The accuracy of defect location is about 1 to 3 cm and the detection depth up to 5 cm.

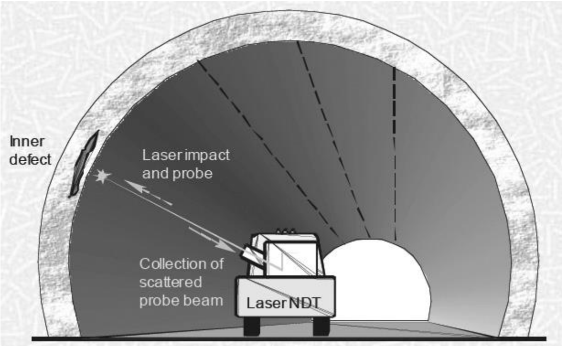

Figure 6. Schematic of the hammer-like laser remote inspection system [49]

2.1.3 Laser Methods

Also of interest is the Tunnelings project [50]. The tunnel inspection system developed by Euroconsult and Pavemetrics, shown in Figure 7, is based on cameras and laser sensors that allow scanning a tunnel's wall linings at speeds up to 30 km/h. The software of the system also allows the data from two different inspection runs to be rapidly compared, and structural changes and wall lining defects to be assessed.

The measurement sensors for the condition survey are installed on a truck capable of running on rails and on flat terrain. The vehicle comprises all the systems necessary for safe road and rail travel (lane occupation indicator, speed governor, electric power supply for all systems, signaling equipment etc.). It can hold up to six laser cameras. Each pair of laser-camera units inspects a 2 m wide section with an accuracy of 1 mm. Using the six cameras, tunnels with a 9 m diameter can be inspected at the system's maximum resolution.

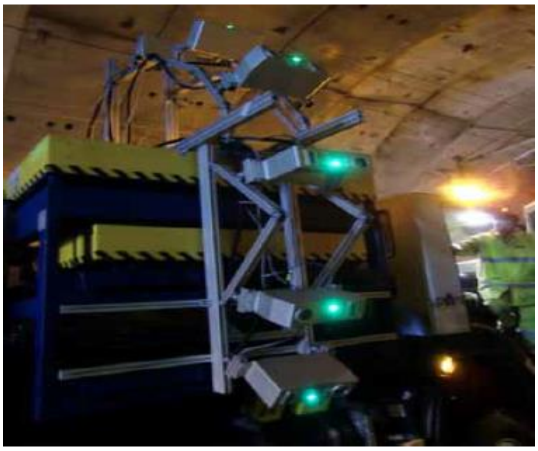

Figure 7. The Tunnelings system sensor structure

The system developed by N. Sano et al. [51] consists in a crack detecting vehicle equipped with laser sensors and CCD cameras. The vehicle is driven through the tunnel by an operator and the cameras take pictures of the tunnel walls. The isolated images taken by the cameras are merged together into a surface map of the tunnel. After the map is obtained, a dedicated vision software detects cracks in it.

2.1.4 Drilling Methods

The system shown in Figure 8 checks for voids behind lining by drilling holes with a mechanized crane [52]. It performs high speed drills of 33 mm diameter by a combination of rotation and striking the lining concrete of a tunnel surface in order to investigate the thickness of a lining and the height of a rear cavity with high accuracy. This example and others (such as methods based on a mechanized hammering tester installed on a crane, Figure 9) were described by Hideto Mashimo and Toshiaki Ishimura in [1], where they define the status of road tunnel inspection and maintenance in Japan in 2006.

Figure 8. Void detection rotary percussive drilling machine [52]

More examples of systems working on Japan tunnels can be found in the work by Toshihiro Asakura and Yoshiyuki Kojima [53], which shows maintenance technology and typical deformation cases of Japanese railway tunnels, along with some methods of inspection and diagnosis and three case studies (Tsukayama Tunnel, Fukuoka Tunnel and Rebunhama Tunnel). The inspection methods examples includes Hammer testing on the lining (performed by an operator in this case), crack measurements in tunnel lining using line-sensor cameras mounted in a vehicle in rails, and investigation of the surface of the tunnel lining using an infrared camera and CCD cameras.

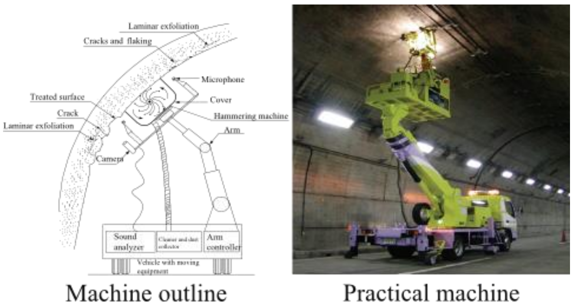

Figure 9. Mechanized hammer test [1]

2.1.5 Tunnel Cleaning

The mechanized cleaning truck shown in Figure 10 is an example of a tunnel maintenance system [54][55], which is important to prevent further damage. It has been designed by engineers of Colas, Switzerland, in collaboration with operators of road networks. It was set up in seven months in 2012.

This tunnel cleaning system consists in a standard commercial truck equipped with eight mechanical arms with different types of brushes. The arms and the brushes have hydraulic actuators which provide movement and water flow for the cleaning process.

Figure 10. Tunnel cleaning system [55]

The mechanical arms can be positioned remotely to adapt to different tunnel geometries. This is achieved with a communication briefcase-like system controlled by an operator near the truck. A second operator is needed to drive the truck at a speed of 2 km/h while the tunnel walls are being cleaned with the brushes. The system can operate in tunnels of a 7.66 maximum height. Only one half of the tunnel section is covered each time, without blocking the traffic on the free lanes.

2.1.6 GPR Methods

Another commercial example is the IRIS Hyrail built by Penetradar [56], shown in the Figure 11. The system is based on a GPR sensor mounted in a telescopic piece in the front of a Hyrail vehicle (e.g. a vehicle able to go on road and on rails). The GPR positioning device can be rotated to cover the sides and top of the tunnel walls and the motorized boom can be retracted to avoid obstructions. Penetradar provides specialized software to manage data collection, data processing and display of GPR data.

Figure 11. IRIS Hyrail system inspecting a tunnel. Note the capability to be mount on rails [56]

2.1.7 Small Tunnel Robots

When tunnels that need to be inspected have reduced dimensions, such as underground tunnels used to deploy power cables, the use of robotic platforms is more than appropriate. In this scenario, small tele-operated mobile robots can make inspections providing visual and concentration data of some poisonous gases, like the system by Fu Zhuang et al. [57] shown in Figure 12.

This tele-operated robot (420mm long, 320mm wide and 300mm high) can operate in 1 meter wide tunnels, move at a rate of 24 m/min, and has 2 hours of autonomy. Its sensor system includes a pan-tilt-zoom camera, inclinometer, gyroscopes, gas sensors (CO, CH_4, CO_2, and O_2), thermometer, IR distance sensors, and ultrasonic sensors.

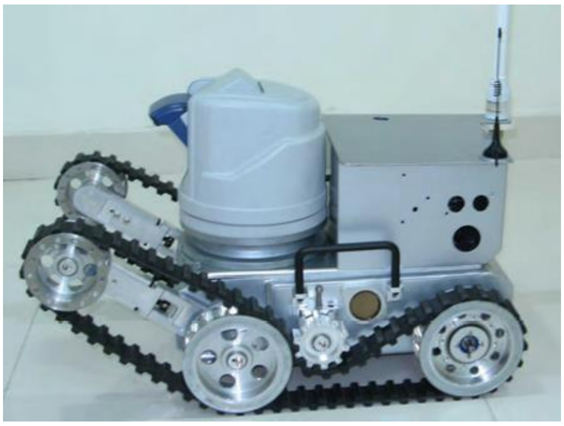

Figure 12. Cable tunnel inspection robot [57]

In other cases, cables are not inside small tunnels but along a greater one placed on the walls. Taking this into account, Songyi Dian et al. [58] designed a robot based on a shrimp-rover vehicle [59] with six wheels able to go over tunnel power cables while making the inspection. Unfortunately, this work is only theoretical and the robot does not exist physically. Other examples of tunnel cables inspection robots can be found in B. Jiang et al. [60][61] and Claudio Mello et al. [62].

Another type of small tunnel is ventilation tunnels. R. Minichan et al. [63] designed three different mobile robots to inspect the ventilation tunnels of the H-Canyon Facility in 2003, 2009 and 2011. Due to the toxic environment of the tunnels, only a robot could perform the inspection process. The control of the robots is made remotely and the system was connected through a long tether to the control station. The inspection consisted in a visual assessment with the images provided by the robot cameras. Figure 13 shows the three robot models.

Not all tunnels are designed to carry vehicles, people or cables. Water distribution is managed with tunnels too, and different solutions must be used to inspect this kind of structures. In this scenario, alternatives to mobile wheeled robots include Autonomous Underwater Vehicles (AUV) [64] and Remotely Operated Vehicles (ROV) [65][66] which can exploit the use of sonar sensors for the mapping procedure.

Figure 13. Three ventilation tunnel robotic inspection systems [63]

2.1.8 Embedded Sensors

All the systems seen in this section have their own sensors, and publish the data obtained to perform the assessment of the structure. However, an alternative strategy involves the use of sensors embedded in the structures to be inspected, such as strain gauges, which are usually more precise and reliable. Brian Esser et al. [67] implemented this method and developed a robot capable of remotely powering and collecting data from a network of embedded sensing nodes, and providing remote data access via the Internet. The system uses Addressable Sensing Modules (i.e. ASM's) to sample data from a wide variety of sensors (e.g. peak displacement, peak strain, corrosion, temperature, inclination, etc.). This kind of system is useful in long tunnels where a wired sensor network is difficult to implement, or in tunnels with complicated access.

2.2 Other Related Robotic Systems

There is also a great number of systems that have been developed for inspection purposes that may be applicable to the tunnel environment. These systems were designed for the inspection of bridges, pipes, or pavement among others. The similarities in geometry, materials, defects and inspection procedures of these systems leads to similar technological solutions able to be used for the tunnel inspection procedure.

Two examples of this kind of robots are the ones designed by Carnegie Mellon. One is a tele-operated vehicle for mapping of abandoned mines [68] (similar in geometry and dimensions to a tunnel). The other is a similar robot, developed for the inspection of hazardous environments with cameras embedded on an articulated arm [69].

Inspection of pipes is also a relevant area. Some pipes' dimensions can be up to 3 m, similar to a small ventilation tunnel. These scenarios involve small tele-operated robots [70][71] able to make visual inspections along with mapping of pipes and deformation analysis [72]. Some of these systems can even perform cleaning [73] and maintenance [74][75][76] operations. Commercial solutions like Redzone Robotics [77] also provide pipe inspection robots.

Certain robots designed for bridge inspection have the vehicle-crane configuration, similar to some of the ones used in the tunnel inspection [1][53][48][78][79], but modified to reach zones under the bridges [80][81][82]. The majority of these systems use the same sensors to achieve the inspection (vision, laser, ultrasound, etc.) and some solutions use robotic arms installed on the tip of the crane to perform maintenance operations [83].

On the other hand, robots designed to inspect the superior part of bridges mainly focus on the crack detection of the pavement [84], and are similar to road pavement inspection robots [85][86][87] that have similar sensors and algorithms to the tunnel crack detecting in tunnels; while others mount a variety of sensors to achieve a more complete assessment [88].

Lastly, climbing capabilities of some robots are being used to perform inspections in zones with difficult access [89][90]. Early attempts used legged robots capable of climbing metallic-based structures [91], while the most modern systems uses suction [92] or negative pressure [93][94][95][96] devices to attach to structure walls.

3 Main Drawbacks

As seen in the previous section, all of the robotic tunnel inspection systems are tele-operated in some way. This is one of the main disadvantages of all these systems. These systems slightly improve the working conditions of the operators in the tunnel, but to successfully overcome all the problems of the manual inspection procedures, a fully automated tunnel inspection system must to be developed.

The need for one or more human operators of the presented systems sometimes require the workers to be in the same location as the robot, eliminating one of the benefits of the robotic inspection, which is remote operation. Because of this, the operator is exposed to the dangerous tunnel environment, including large isolated areas, low visibility, dust, humidity or even toxic gases.

In some cases, the inspection data gathered by the system is not enough to make a complete assessment of the tunnel, and an additional manual inspection performed by a qualified inspector is required. This causes subjectivity in the inspection results that relies on the inspector judgment and may contain diverse errors.

In other cases, the limitations in the type of communication used (e.g. tether length, wireless area) leads to the same problem described before. In the case of wired tele-operation, the main bottleneck is the length of the cable itself, which limits the operational range of the robot with respect to the control station.

Regarding the wireless communication, one problem is the signal intensity decay, and it could depend on the tunnel length, material or complexity. Other problem is the bandwidth that needs to be high if the robot has little autonomy and sends a large amount of data to the tele-operator.

The difficulties mentioned before mainly affect the quality of the inspection and the operators working conditions, but an important aspect of the inspection procedure is the economic impact that is incurred when a tunnel must to be closed for inspection. Leaving the tunnel inoperable reverts in losses for the tunnel owners and users. Because of this, taking into account this issue is desirable to develop systems that can allow the use of the tunnel during the inspection procedure.

One of the solutions to these problems begins with the improvement of the automatic behaviors of the robots. With a fully automated inspection system, the security of the operators is guaranteed, along with the management, quality and objectivity of the tunnel data. Current efforts should be focused on obtaining more autonomous behaviors that may adapt to different tunnel environments with less operator dependency.

4 Current Efforts in Fully Automated Tunnel Inspection

The latest developments in robotic and automation science allow the current tunnel inspection systems being developed to become more automated than the previously seen tele-operated systems. This confirms that the tendency is to reach a fully automated inspection system that allows a remote inspection with no direct human operation needed.

The first part of this section reviews the TunConstruct system, which was partially autonomous, while the second part explains the ROBINSPECT system, which aims to perform fully automated tunnel inspection.

4.1 TunConstruct System

The TunConstruct project [78][79] was part of the European Commission 6th Framework Program (FP6), and was conducted by 41 partners from 11 European countries. The main objective of the TunConstruct project is to reduce the cost and time of construction of underground infrastructure, promoting the sustainability of our environment and the safety of people during the phases of construction and use of services and infrastructure.

In order to contribute to the general objective of the project, several different engineering applications were developed. One of these proposals involved the development of a robotic system capable of performing inspection and maintenance in concrete tunnels.

4.1.1 Maintenance Procedures to be Automated

Presently, as with the inspection procedures discussed previously, practically all maintenance operations in tunnels are performed manually. This leads to similar disadvantages: traffic flow must be cut, and scaffolds mounted, implying the subsequent loss of global productivity. The aim of the TunConstruct project was to automate these procedures to overcome the mentioned drawbacks. The maintenance operations automated inside the scope of the project call for the following set of tasks: superficial preparation, fissure injection, and FRP composite adhesion.

- Superficial preparation includes all of the processes needed to eliminate concrete in bad state. The surface must be prepared before the reparation process. Common methods include compressed air blowing, sand abrasion, and hydrodemolition.

- The main objective of the fissure injection is to re-establish continuity in concrete sections. The material used to fill the concrete discontinuities is usually low-viscosity epoxy resin. Injections can be used to fill in internal or hard-to-access zones.

- Superficial reparation and restoration with Fiber Reinforced Polymer (FRP) has progressively increased in use. Carbon or aramid fibers allow high mechanic, thermal, electric and chemical resistance, high modulus of elasticity, and low density [97]. To apply the fibers on the concrete surface, a layer of epoxy resin is propagated across the surface. Next, the fiber strip is placed over the resin and pressed against the surface. After this, a finishing layer of the same resin used before is applied over the FRP.

4.1.2 TunConstruct System Components

The TunConstruct system, shown in Figure 14, consists in a robotic arm on the tip of a crane, mounted on a vehicle. The robot arm chosen for the application was the Mitsubishi PA-10, a 7 DOF manipulator with 10 kg load capacity and 1 meter maximum extension range. The global increment of this range is achieved by mounting the robotic arm on a 5 meter extensible articulated lift platform.

A HMI is installed in the wheeled vehicle's cabinet to which the articulated lift platform is attached. Power for the system can be supplied from an on-board generator, the wheeled vehicle's motor, or the tunnel's basic provided services.

A lightweight sensed integrated tool was designed and manufactured for the automation of the described processes. A conceptual design of the mentioned tool can be seen in Figure 15. The tool is composed by two complementary systems: a material application system composed by mechanical subsystems and actuators, and a vision and security system composed by camera, laser distance sensor, and security micro-switches.

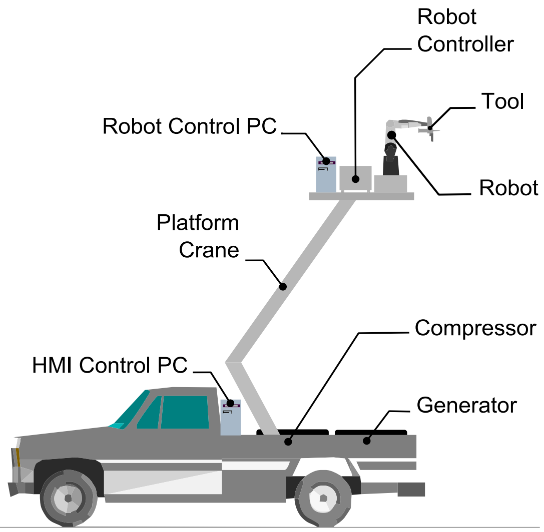

Figure 14. TunConstruct system scheme

The option chosen for superficial preparation was compressed air blowing as selected and existing composites must be applied on dry and clean surfaces. An on-board compressor mounted on the wheeled vehicle provides the compressed air. Air flow is digitally controlled by low power-consumption mini-electrovalves.

The fissure injection procedure uses a nozzle that is an empty cylinder with one resin input bore (ϕ 5 mm) and many punctures (ϕ1mm) for the tunnel side. The availability of compressed air implies that the thrust of the resin towards the tip is triggered by the canalization of compressed air towards the piston of the resin cartridge.

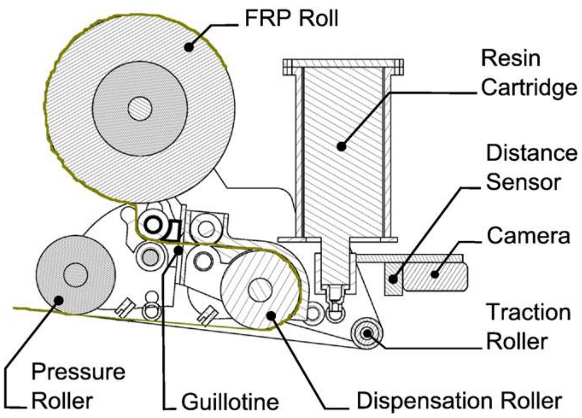

Figure 15. TunConstruct tool diagram

Regarding the fiber application, a gear-and-roller-set system was designed for the dispensation of dry FRP strips. Motion is achieved through the rotation of a roller by friction with the surface to obtain compact resin–FRP–resin layers mounted on the tunnel's surface. In order to cut the roll of FRP into strips of the desired length, the gear-and-roller system is combined with a guillotine-like cutting mechanism that is activated by relative movements between the tool's internal mobile parts and the tunnel's surface. A transversal section of the tool performing FRP application can be seen in Figure 16, where FRP describes the red trajectory, resin output is set in blue, and additional resin-flattening trowels are circled in orange.

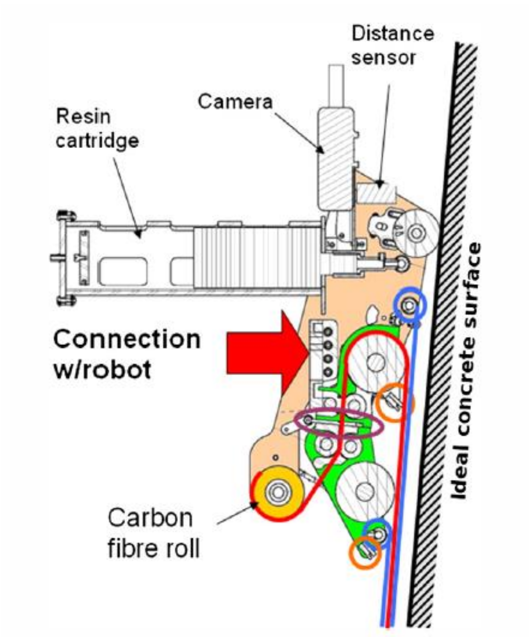

Figure 16. FRP application process

An Axis IP surveillance camera and an ultra-light precision laser telemeter sensor are the two main components of the vision system. Sensor ray and the camera's central pixel point are aligned and oriented parallel to the axis of the resin cartridge. Microswitches activated by contact with the tool's mobile parts assure mechanical safety.

4.1.3 Inspection and Maintenance Procedure

Once in the tunnel, the operator places the vehicle behind the zone to be repaired. The inspection is performed through a user-friendly guided HMI (Human Machine Interaction), where the camera image stream is displayed and operation procedures are requested. Visual servoing based on the depth measure captured by the tool’s laser telemeter, and operation-oriented actuators are coordinated through task-specific control software, allowing the process to be automatically performed by the robotic system.

Using the HMI with the images provided, the operator can guide the robot and select the crack in the tunnel surface in which the system is going to apply the repair material. Two options are available: superficial preparation and epoxy resin injection, or superficial preparation and FRP adhesion.

Figure 17 shows the program main screen. A virtual traffic light (circled in red) informs the user if the tool tip is too close or too far away from the tunnel surface. The exact measure of the distance from the tool tip to the surface is also presented to the user.

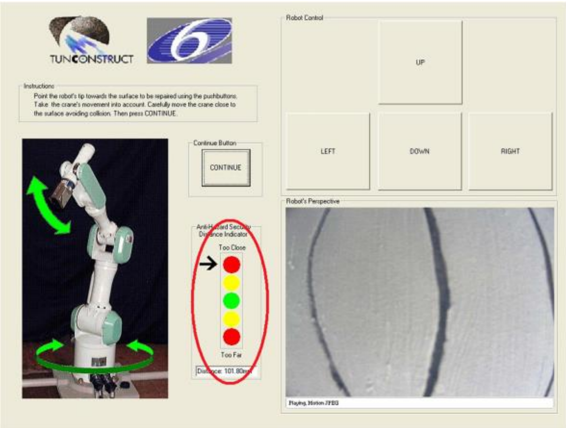

Figure 17. TunConstruct interface

In the first main screen, two degrees of freedom are permitted to the operator for directing the robot. User is intended to direct the end-effector tool perpendicular to the position of the surface to treat. The operator, when satisfied, presses the CONTINUE button. A zoomed vision of the camera images is displayed, and fine adjustment of the robot tip is performed with the same degrees of freedom.

After proper positioning of the robotic arm, the user is allowed to mark the points of interest for trajectory generation. In FRP adhesion procedure, the operator marks the limits of the FRP strip to be adhered. In resin injection procedure, a spline-type curve is generated as operator marks points through the interface.

The 2D data introduced by the operator is enough for the system to generate the final 3D robotic trajectories. The system executes these trajectories while coordinating the automatic actuators for task completion. The operator simply waits for procedures to be performed. After task accomplishment, the robot safely returns to its initial position, and the interface returns to the main screen.

Communication schemes between HMI and control software are implemented over TCP/IP, the Internet Protocol. This means the operator could technically run the HMI software to identify fissures and weakened surfaces from any place in the world.

4.1.4 System Testing

The TunConstruct system was first tested indoors, using models manufactured by FRP and epoxy resin providers. After having succeeded in proving effectiveness in all of the laboratory tests, the complete integrated system was taken and tested outdoors. Demonstrations were performed in real, non-controlled environments in tunnels in Bembibre, León. There too, tests provided satisfactory results in terms of human–machine interaction, robot trajectory generation and task execution. A demonstration of how vehicles can pass below the system while process operation is being performed in a functional tunnel can be seen in Figure 18.

Figure 18. TunConstruct system test in a Spanish tunnel. Note that one lane of the tunnel traffic flow is not blocked

4.2 ROBINSPECT: Towards a Fully Automated Robotic Inspection System

ROBINSPECT (ROBotic System with Intelligent Vision and Control for Tunnel Structural INSPECTion and Evaluation)[1] [98] is a project co-funded by the European Commission, under its 7th Framework Program (FP7). The project begun on October 2013 and will finalize in 2016. This project comprises the design of an autonomous robotic system capable of performing intelligent inspection and assessment of a tunnel in one pass. Figure 19 depicts a schematic representation of the ROBINSPECT system. Its similarity with previous projects of the field is in line with a "not reinventing the wheel" philosophy, and instead focusing on automation, intelligence, and benchmarking objectives.

ROBINSPECT is driven by the tunnel inspection industry, and adapts and integrates recent research results in intelligent control in robotics, and computer vision tailored with semi-supervised and active continuous learning and sensing, in an integrated robotic system. The final system is intended to scan automatically the tunnel intrados for potential defects on concrete surfaces and be able to detect and measure radial deformation in cross-sections, distances between parallel cracks, and cracks and open joints that affect tunnel stability, with millimeter accuracies. This will allow, in one pass, both the inspection and structural assessment of tunnels.

[1] http://www.robinspect.eu/

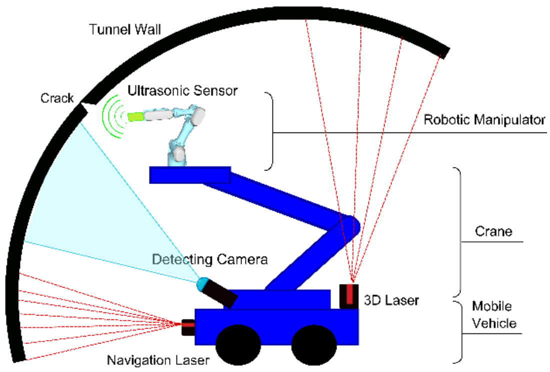

Figure 19. ROBINSPECT schematic representation

The initial dataset on tunnel defects has been provided from case studies (including London Underground, an interesting case study as the network incorporates the world's first underground railway) to be used not only for transfer learning but also for the evaluation of structural models. The robotic system will be evaluated and benchmarked at the research infrastructure of tunnels of VSH in Switzerland, at three road tunnels of the Egnatia Motorway in Greece, and sections of the railway tunnel of London Post Office.

4.2.1 ROBINSPECT System Components

The ROBINSPECT extended mobile robotic system consists on a wheeled robotic system 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 and sensors (see Figure 19). The mechanical components of the system consist of a mobile vehicle, an automatic crane and an industrial quality robotic arm placed on the crane platform. Systems with similar configurations are the TunConstruct system [78][79], and other existing systems of the construction industry [99]. The two sensor subsystems consist of various cameras with artificial vision algorithms for cracks detection and an ultrasonic system for characterizing cracks.

The crane of the vehicle is sensorized in order to control the platform's position and orientation. To enable collision avoidance, localization and navigation, the mobile robot includes two laser sensors and a digital camera. The mobile vehicle laser sensor will be combined with visual landmarks detected with the camera, to be able to distinguish amongst different similar sites inside the tunnel. Special attention has been placed in keeping the vehicle stability as well as developing the platform modular enough to allow both road and railway navigation. A set of landmarks placed along the tunnel and dedicated cameras and laser sensors have been attached to the mobile vehicle in order to achieve an accurate path following in tunnels.

The robotic arm chosen is the Mitsubishi PA-10 (see Figure 20). This model was used successfully in the TunConstruct project described on section 4.1. The range of movements of the robot covers from few centimeters to one meter approximately. A processing PC will be used to run all the software needed to the correct operation of the arm and can be placed either inside the platform or attached to the mobile vehicle depending on the mobile vehicle space availability. This PC is connected to the servo driver controller. The control software is based on the ROS [100] software architecture used also on the mobile vehicle. In addition, some modules communicate internally using YARP [101] libraries. The robotic arm system uses an external 2D range laser sensor in order to compute the required trajectories during the inspection process. This laser could be mounted in the platform near the robot base or attached to a link of the arm.

The visual sensor system consists in three different parts:

- A 3D laser profiler located on the mobile vehicle. Using this laser a slice of the tunnel lining will be scanned. This 3D surface will be used to detect lining deformations.

- A full-frame DSLR camera mounted on the mobile vehicle will take images of the tunnel walls in order to detect cracks and other concrete defects.

- A structured light system consisting in a pair of stereo cameras and a projector attached to the robotic arm. These devices will provide a detailed 3D image of the defect surroundings to the tunnel assessment module.

A special new ultrasonic sensor developed by one of the project partners will be mounted on the robotic arm of the robot and will be displaced on the tunnel wall during the ultrasonic measurements. The sensors will be positioned in vicinity of the crack at a controlled distance from it in order to take crack width and depth measurements.

Figure 20. PA-10 robotic arm

Apart from the mentioned components, ROBINSPECT will use a Ground Control Station (GCS) device and a control room. The GCS includes a graphical user interface to control high-level aspects of the system and it is connected via Wi-Fi to the robot. The control room receives all the inspection data and performs the tunnel assessment using a set of software tools developed inside the project scope.

4.2.2 ROBINSPECT Inspection Procedure

Regarding the inspection procedure, the vehicle positions itself at a constant distance to the wall (using the navigation laser sensors), and then advances with constant velocity parallel to the tunnel wall while the inspection is performed. This first inspection level is based on visual detection using the images provided by the DSLR camera.

When a tunnel defect is detected, depending on the type of defect, the system stores the position and type of the defect and continues the movement, or stops to take additional measurements. If the defect requires more measurements, a second level of inspection is performed. The additional data will come from the laser profiler installed on the mobile vehicle and/or the cameras attached to the robotic arm. The laser can provide 3D point-cloud data of the actual tunnel section, while the cameras can take closer pictures of the defect.

Additionally, if the defect is a relevant crack, the crane-robot subsystem will approach to the crack. Then, the robotic arm controllers will compute a safe trajectory to approach to the crack using the input from the robotic arm laser placed on the crane platform. Finally, the robot performs the trajectory at low speed to avoid excessive oscillations of the system and ensure the sensor's integrity. When the ultrasonic sensors attached to the robot tip are in contact with the crack, they measure the crack characteristics (width and depth particularly). At this point, the stereo cameras extract 3D information of the crack surroundings.

When all the relevant information is extracted, the robotic arm and the crane return to the initial position. The system then returns to the first level inspection state and the mobile vehicle restarts the movement. All the described processes are repeated until the tunnel is fully inspected or the user stops the system.

4.2.3 Robotic Controllers

At the software level, Component Based Software Engineering (CBSE) techniques are being applied. Specifically, a set of low-level device drivers for each of the robotic subsystems has been 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 [101], ROS [100], OROCOS [102], etc.) for implementing CBSE exist and are interoperable.

During the development of the robotic software components, ROS and YARP have been used to program the low-level drivers of the robotic arm. The drivers allow the robotic arm to be controlled either in position or in velocity. In addition, the use of the ROS environment allow the controllers to communicate easily with other software tools responsible for trajectory generation, and to receive orders from the high level controller.

A global controller for the system in the presented scenario will be developed for two main reasons. Firstly, the additional length requirement means that any deviation of the control output at any of the stages of the low level will be multiplied at the end-effector of the robotic manipulator (sensing tip). Secondly, the three different mechanical subsystems (the mobile robot, the automated crane arm, and the robot manipulator) must fulfill a set of required behaviors conjunctly. Then, only a global controller can assure coherent and optimized trajectories.

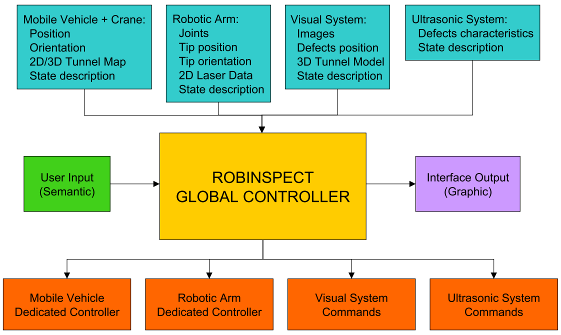

Figure 21. ROBINSPECT global controller architecture

Moreover, the input of this global controller will come from the vision, laser, and ultrasonic sensor systems, and the mechanical state of the mobile vehicle, crane, and robotic arm. A diagram of the controller inputs and outputs is shown on Figure 21. The global controller incoming data will be very different in nature and consists in:

- Visual information consisting in images labeled by the computer vision algorithms and 3D position of the detected defects
- An online stream of updated 3D model data of the tunnel environment coming from the 2D and 3D laser sensors and the stereo camera system
- Associated uncertainties (both intrinsic to the nature of the sensors as information regarding the confidence at each given instant) of the 3D data
- Position and orientation of the mobile vehicle, crane and robotic arm systems
- Additional semantic information regarding the state of each of the system components and the required action or behavior coming from the user interface

To manage all the different data and generate proper commands, an intelligent controller will be developed as the global controller. It will update its prior belief model of the tunnel environment continuously by using the 3D model stream data 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.

Additionally, the system's safety for the robotic system and environment is 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).

5 Future Trends

The previous sections have presented an extensive review on tunnel inspection methods and robotic systems with tele-operated and more modern approaches focusing on the structural inspection problem. A discussion is open in this section, in the context of presenting solutions based on forthcoming improvements in the robotics area and related fields, in order to have a more complete vision of the future trends of technology and new approaches.

In terms of complex and unstructured environments, the great majority of large inspection systems cannot work properly, or have difficulties in doing so because of the use of wheeled platforms. One possible solution could be the use of legged robots with insect-like legs, such as the proof of concept robotic harvest system developed by John Deere [103] or the quadruped robot built by Boston Dynamics [104], to go through rough and uneven terrain and avoid unexpected obstacles easily.

Another technology applicable to the future tunnel inspection process that avoids the mobility limitations are the Unmanned Aerial Vehicles (UAV) developments. There are some works that start to use this approach [105][106]. One advantage is that these robots may be produced at low cost, and used simultaneously as they do not interrupt traffic. A complete swarm of robots with reduced dimensions may be used to perform the inspection process faster and exhaustively, concurrently gathering large amounts of data. Figure 22 depicts a hypothetical tunnel inspection scenario using legged robots and UAVs.

A more advanced notion of legged robots would be the use of humanoids and anthropomorphic robots. Advances within the field of robot walking gait generation and solving stability issues are required for this step, but it is favored in turn with the advantages of the capabilities of these robots, which have the potential of using the same vehicles and tools that human workers currently employ, without exposing humans to the associated risks.

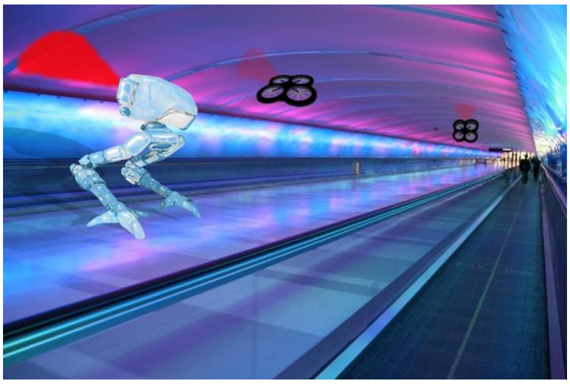

Figure 22. Conceptual image of a future tunnel inspection process[2]

On the other side, reducing robot dimensions with advances in the field of nanotechnology could lead to a different type of inspections in the future, using nano-robots, a.k.a. nano-bots. These nano-mechanisms could penetrate tunnel walls through cracks or small fissures and perform inspection and structural assessments of the materials from the inside, or search for invisible cracks in the extrados. Tests that are currently destructive could be performed through the use of non-destructive nano-bot mechanisms.

In terms of including preventive measures within the design phase, another good idea is to take into account the inspection and maintenance processes at the time of the structure construction. A set of rails could be planned and located along the tunnels, ready to a rail-robot to be attached. In this way, the robot (e.g. a robotic arm with sensors at the tip) may travel around the structure and inspect it with different sensors. Additionally, the robot could store different tools and sensors, and only pick up the appropriate ones when required for a given tunnel structural assessment.

Predictive efforts should benefit from advances in sharing and storing big data and information theory. Tunnel data can be saved and retrieved, and this process should become globally accessible through integrated services. Data may be used to compare different inspections of the same tunnel or similar tunnels around the world. Information from nearby and similar structures could be used to infer an idea of the land movements and predict how this will affect to the structures.

[2] Original background photograph by Scott Beale

6 Conclusions

Although great efforts are being made in the robotics community, existing robotic tunnel inspection systems today suffer from a number of drawbacks that must be overcome. Most of the systems described are totally or partially teleoperated, which requires an operator to be in an uncomfortable and dangerous environment. Additionally, in some cases, the information obtained from the inspection is not enough to make a full assessment of the tunnel, and additional inspections involving human operators are required. In addition, the data obtained is processed after inspection sometimes, extending the time of obtaining the results and exposing the tunnel to accidents if there is any major deficiency.

One of the major solutions to these problems is to make the system fully autonomous. This is the goal that is being pursued in recent developments such as TunConstruct and ROBINSPECT projects. A completely autonomous system can perform the inspection of the tunnel without compromising the safety of operators. Regarding the finalized TunConstruct project, it was possible to develop a semi-autonomous system capable of applying a treatment to repair cracks. Regarding the ROBINSPECT project in development, the main goal is to traverse the tunnel environment autonomously and detect and characterize defects and then send the information to a control station, where the data will be collected for comparison with previous inspections to make a complete assessment of the tunnel.

Future systems must be capable of both maintenance and inspection with minimal human intervention, and perhaps with no supervision at all. Much research is ongoing in able to design better systems, capable of performing accurate and cost-effective inspection, maintenance and assessment of civil structures that reverts in more safety in environments and less budget spent in reparations.

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