

A Robotic System for Fire Fighting in Tunnels

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Abstract—The problem of safety in tunnels is considered, with particular concern to the vulnerability to fire. The important role that robotics may play for fire fighting and preventing is outlined and a robotic system, purposely designed for tunnels, is presented. The system can be installed in most of the existing tunnels without requiring significant modifications of the existing infrastructures. Moreover, it may guarantee a rapid and selective intervention in case of accidents in both road and railways tunnels. The main features of the system are illustrated and some details about the mechanical structure are provided. The results of the dimensioning procedure of the robot actuators and of the energy supply are also given, which confirm the feasibility of the robotic system.

I. INTRODUCTION

The problem of safety in road and railway tunnels and, in particular, the risk connected to fires has become of particular concern after some recent tunnel disasters. The impressive images of the 1999 fire in the Monte Bianco tunnel (connecting Italy to France), and of that in the Tauern tunnel (Austria) are still on people's mind [1], [2].

The lesson learned is that the capability of intervention of firemen in tunnels is very limited because of the extreme environmental conditions (high temperature, intense smoke, gas emissions, traffic, rails and other obstructions) which delay or preclude the action of men and machines. On the other hand, a prompt and effective intervention is crucial to keep the fire under control and contain the damage.

Tunnels are important infrastructures for the European Union and play a crucial role for the development of the regional economies [3]. However, most of the existing tunnels in Europe do not have a safety system adequate to the actual traffic volume, which is continuously increasing. For this reason, the risk of serious tunnel disasters is significantly higher than in the past years and their costs become more and more relevant.

As a matter of fact, technology may give a precious support to augment safety in new or existing roads and railways tunnels. Tunnels can be made intelligent by using distributed sensors to measure significant variables (temperature, humidity, wind velocity, presence of smoke or other gases, etc.) that can be collected and suitably elaborated to facilitate human intervention or to guide the operation of automatic devices [4].

In this work, the main structural features of the existing tunnels, as well as of the most important European regulations concerning safety, are surveyed. Moreover, a state of

the art of the technologies developed for prevention and/or fighting of fires in tunnels is briefly presented. Then a new robotic system, purposefully designed to guarantee a rapid intervention and continuous water restocking, is proposed.

The system is based on the ROBOGAT patent [5] and is the subject of a National Operational Program (P.O.N.) financed by the Italian Ministry of Education, University and Scientific Research. The project is currently under development. In this paper the main features of the system are described and the research issues, motivated by the challenging task of fire fighting in tunnels, are outlined. Details about the mechanical structure and the dimensioning of actuators and energy supply are also provided.

II. THE OPERATIVE SCENARIO

The robotic system presented in this paper should be installed in existing tunnels, with minimum necessity of structural modifications. Thus, it is important to briefly illustrate the main characteristics of the tunnels and the laws and regulations concerning tunnel safety.

Tunnels can be roughly classified into road, highway, and railway tunnels. Some of them may be very long (as San Gottardo tunnel, which is 16918 m long) and connect different countries (as Monte Bianco tunnel, 11600 m long). The geometric features that characterize a tunnel are: length, transversal section, altimetric profile and planimetric development. Tunnel structural components includes the number of tunnel tubes and lanes, the lay-bys and the equipments (illumination plants, ventilation plants, traffic signs, video surveillance plants, fire extinguishing plants, water drainage channels, etc.).

Ventilation is of major significance with respect of preventing or limiting dissemination of smoke and toxic gases in the event of a fire. Ventilation systems comprise: structural components (roof ducts, intake and output channels, ventilation plants), mechanical equipment (fans, reversing plates and flaps, silencers, dampers), electronic and electric equipment (actuators, monitoring sensors, control units). Depending on tunnel length and type of traffic, four types of ventilation systems can be used: natural ventilation, longitudinal ventilation (using jet fans), semi-transverse and transverse ventilation (with ducts used to supply fresh air and extract exhaust smoke).

The transversal section of a tunnel should allow the installation of all the equipments and the free section

has to respect security margins in the vertical and lateral directions. An example of section is reported in Fig. 1.

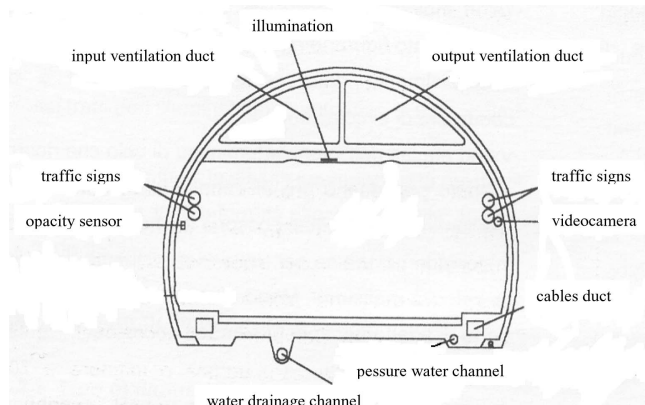


Fig. 1. Example of cross-section of an equipped road tunnel.

Public administrations specify safety requirements in the forms of guidelines and regulations that are applied to all the tunnels of the same class, in order to attain a similar degree of safety. In view of the large numbers of interdependencies of elements relevant to safety, measures for the infrastructures need to be carefully coordinated.

As an example, for the case of a road tunnel out of urban areas with two ways, length between 2 km and 3 km, free section more than 3.5 m high and base length between 8 m and 9 m, the Italian regulations require the presence of sidewalks on both sides, emergency exits, safety recesses and fire extinguishing equipment every 200 m and lay-bys every 800 m; moreover, the following safety equipment are required: continuous power supply and current plugs in the safety recesses, ventilation plants (longitudinal ventilation with jet fans at 600 m distance or semi-transverse ventilation with extraction ducts at a distance between 50 m and 100 m); emergency lights and light signs and signals every 10 m on both sides, telephones in the safety recesses and along the emergency exits; 2 fire extinguishers in all the safety recesses; water supply every 200 m by one side; fire detectors, radio communication, variable message signs; video monitoring systems in case of human surveillance.

The regulations about rail tunnels are quite different from those of road tunnels, even though the structural installations and the safety measurements are very similar. For brevity, in this paper only the case of road tunnels is considered.

In tunnels, the number of accidents is often lower than outside, mainly because the road is not exposed to adverse weather conditions such as snow, ice, wind and rain. However, the extent of harm to users in the event of accident in a tunnel is far greater than in the case of an open road, especially in the presence of fire. Due to the fact that tunnels are enclosed spaces, fires occurring in them result in poor visibility, spread of smoke and toxic gases along the tunnel, rapid development of high temperatures (up to more than 1000°C) and reduction in the level of oxygen in the air.

Several studies have been carried out to investigate the behavior of smoke and temperature in tunnels under a range of different structural characteristics and operating conditions [6], [7]. The smoke is one of the principal cause of death and also makes the intervention of the fire brigades very difficult. The combustion of a vehicle reaches the flash-over (i.e., the condition where all the inflammable material is on fire) after some 7 to 10 minutes after the beginning of the fire. In real cases it happened that the propagation of flames occurred up to 40 m distance, while smokes and sparks arrived up to 500 m.

III. CURRENT SOLUTIONS FOR PREVENTION AND INTERVENTION

Four crucial points are usually considered for prevention of accidents and fires in tunnels: the behavior of the road users, the vehicles characteristics, the type of infrastructures and the operation of the tunnel infrastructures.

The behavior of the road users is the main factor influencing safety in tunnels. There are various ways in which it is possible to influence the road users behavior, which include education, driving instructions and provision of information using, for example, variable message signs.

The way in which a vehicle is constructed also plays its part in fire prevention. In fact, according to international statistics, a majority of vehicles fires are not caused by an accident, but from self-ignition of the vehicle or its cargo, due to defects in the electrical system, overheat engines, etc. Hence, the use of materials which are not easily combustible should be recommended, as well as the reduction of quantity of fuel carried by heavy vehicles or the adoption of heat detection equipment as well as fire extinguishing equipment.

The tunnel infrastructures must satisfy a certain number of national guidelines and regulations, possibly internationally coordinated.

From the operation point of view, a large number of duties are in charge to tunnels operators (monitoring of the efficiency of all the installations and equipments) as well as traffic police (operation of traffic control systems, organization of emergency services and information to road users) and emergency services (fire fighting, rescue and medical assistance, restore of normal conditions).

Different advanced solutions have been adopted in the last years in European tunnels to prevent fire. They are essentially based on distributed monitoring systems including fire detection systems (based on smoke and temperature sensors and on infrared cameras) and traffic monitoring systems. Examples can be found both for the case of road tunnels [8] and railways tunnels [9]. In some cases also a thermal control of the vehicles at the entrance of the tunnel is performed, as for the thermographic portal of the Frejus tunnel [10]. It allows detecting suspect temperatures of the various components of a vehicle, such as brakes, transmission drives, tires, motor, etc., as well as on the charge of trucks, while the vehicle is in motion. This is

achieved by using suitably disposed infrared sensors, as well as standard visual sensors, which perform a first check on the vehicle in transit; if a potentially dangerous situation is detected, the vehicle is checked more in depth using infrared cameras and water jet to refresh hot components.

An example of tunnel including the most recent achievements of the research on safety in Italy, is the Naturno tunnel. This is a double tube tunnel of 2500 m length, equipped with a supervision system operating 24 hours per day (with the human presence in a remote control room) controlling all the technological equipments in the gallery, i.e., ventilation, environmental sensors, safety, emergency devices, fire fighting equipment, traffic lights, electric power. The main operations carried out by the supervision system are: traffic monitoring so as to prevent possible causes of accidents; management of the traffic density and velocity; communication of traffic restrictions to drivers; monitoring of all the equipments of the tunnel; alerting of emergency services in case of accident; indication of the exact location of the accident with the potential fire; detection of smoke and dangerous gases; monitoring of the visibility conditions; execution of preliminary emergency operations; starting of the evacuation plan.

A functional architecture of the supervision system of the tunnel is reported in the Fig. 2.

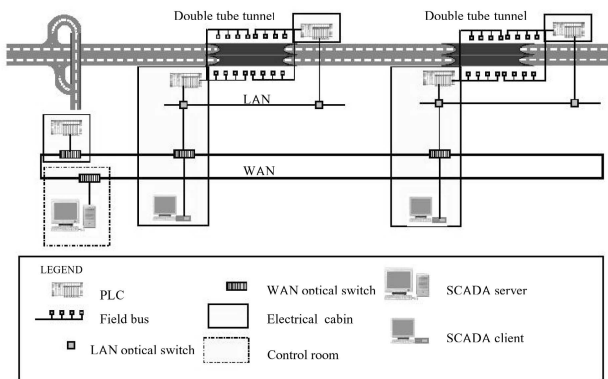


Fig. 2. Architecture of the supervision system and data acquisition (SCADA), automation and telecontrol.

From the intervention point of view, several tunnel fire protection systems have been devised. As an example, fixed installations can be adopted, composed by fire foam emitters or deluge systems distributed along the tunnel, which can be eventually divided into sections; in case of detection of fire or high temperature smoke, the interested section is invaded by fire extinguishing material in order to facilitate the intervention of firemen [11].

The efficiency of fixed plants has been largely discussed during the last years. They are used in Japan in all tunnels longer than 10 km or tunnels with more than 3 km length and high traffic density; in Europe and in North America up to now only very few applications can be found. Without any doubt those installations can significantly contribute to

avoid spreading of fire to queuing cars behind the place of the original fire. But, on the other hand, critical points concern the significant deterioration of escape conditions, the production of masses of hot vapor in addition to the smoke, the choice of the time and location for the activation of the system, and the availability of an adequate reservation of extinguishing material.

In sum, the prevention and the fixed intervention plants allow mitigating but not eliminating the crucial problems connected to fires in tunnels, i.e., access difficulty, difficult supply of water or other fire extinguishing substances, critical environment conditions.

A possible solution is that of designing a robotic system able to perform operations similar to those of firemen, without the above mentioned limitations. This system is based on the ROBOGAT patent [5] (see Fig.3), which is a robotized system composed by a fixed plant, as a monorail, used for robot locomotion and water supply, and a mobile part, represented by a vehicle moving on the monorail and a robotic arm carrying fire fighting devices. This solution solves the accessibility problem, because the monorail may be installed on the side or on the ceiling of the tunnel. Hence the vehicle may reach any point of the tunnel in short time, guaranteeing a prompt intervention (as an example, with a cruise velocity of about 60 km/h, the vehicle may traverse the whole Monte Bianco tunnel in 12 minute time). Moreover, it guarantees a selective fire fighting action, which allows mitigating the difficulties of the fixed plants as well as of the fire brigades. For long tunnels, it could be convenient to install multiple robots from both sides or in intermediate positions, so that more robots may reach the fire place in shorter time.

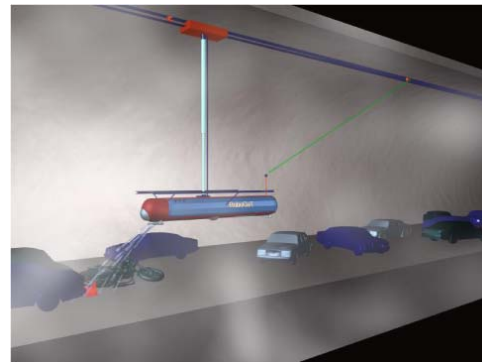


Fig. 3. The robotic fire-fighting system (ROBOGAT patent).

IV. SYSTEM DESIGN AND DIMENSIONING

In this section, the details of a prototype of robotic system based on the ROBOGAT patent are given.

The monorail has a double T cross-section which includes a pipe of suitable diameter, carrying high pressure extinguishing liquid. The pipe is connected from both sides to a water (or other liquid) supply and a pumping system which guaranteed continuous water restocking and allows

model of the robot is very important for dimensioning the actuators and the batteries, as well as for optimal trajectory planning.

B. Actuators

The robot actuators are chosen as three-phase asynchronous motors for the mobile base. The velocity of the asynchronous motors can be controlled by acting on the frequency of the input voltage, while the maximum torque depends on the ratio between the voltage amplitude and frequency. An inverter is adopted to achieve a voltage of variable amplitude and frequency, by resorting to a PWM technique.

In order to avoid saturation of the magnetic circuit at starting, the asynchronous motor will be controlled at constant torque instead of constant power.

For dimensioning the motors used for moving the mobile base, the maximum velocity, the maximum initial and final accelerations (assumed to be of the magnitude), as well as the maximum power and torque must be taken into account.

Considering that the incubation time of a fire is of the order of 15 minutes, and that, to contain the damage, it is advisable to be on the place of the fire in 6 minute time [4], the mean velocity can be easily computed. For example, for the Monte Bianco tunnel (11.6 km), assuming that the fire happens at the center of the tunnel, the mean velocity $\bar{v}$ is about 60 km/h. The maximum velocity v_M , by taking into account the starting and stopping phases, can be estimated as at most 20% higher than the mean velocity, i.e., 72 km/h.

The maximum acceleration should be chosen so as to avoid slipping of the robot on the monorail and motor overload. Considering a value 0.3 for the adhesion coefficient of the wheels on the monorail, a reasonable value for the maximum acceleration to avoid slipping is about $0.3g = 2.9 \text{ m/s}^2$; the constraint imposed by the motor overload depends on the vehicle trajectory and will be considered in the following.

To the aim of choosing the vehicle trajectory, it is useful to compute the limit velocity and acceleration profiles for assigned maximum torques of the motors, vehicle inertia, aerodynamics forces and friction.

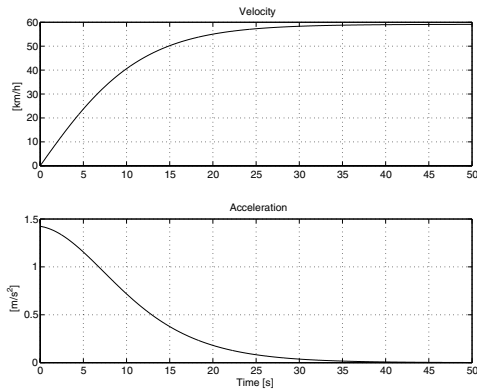


Fig. 5. Profile of maximum velocity (top) and acceleration (bottom).

A convenient choice of the vehicle trajectory may be that of choosing the velocity profile of pseudo-trapezoidal shape with cubic blends. This choice ensures null initial and final values of both velocity and acceleration; moreover, it allows respecting in a simple way the constraint on the maximum velocity and acceleration. For example, for a given maximum velocity, from Fig. 5, the maximum acceleration can be computed, i.e. the acceleration corresponding to the maximum force. These values are the constraints to be imposed to the vehicle trajectories. Once that the maximum acceleration and velocity are chosen, the minimum time trajectory can be computed using a velocity profile of pseudo-trapezoidal shape with cubic blends (see Fig. 6) and adopting the design methodology reported above. The corresponding power and torque can be computed by using the dynamic model of the robot (including the actuators) as reported in [13]; it can be verified that all the quantities satisfy the design constraints.

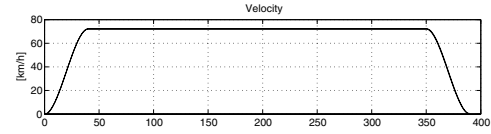


Fig. 6. Time history of the velocity for a minimum time trajectory.

The actuators used for the robot carrying the monitor are chosen as brushless motors, which offer a high range of velocities and accelerations with small weight and volume, as well as high positioning accuracy.

The dimensioning of the brushless motors can be made by computing the maximum torque and power required for a particular demanding manoeuvre (in terms of power requirements). The selected manoeuvre corresponds to a situation where the mobile base (joint 1) has to advance by 10 m in the forward direction, joint 2 must rotate from 0 rad to $\pi/4$ rad, and joint 3 must rotate from $-\pi/2$ rad to $\pi/4$ rad. For each joint, a trajectory with a velocity profile of pseudo-trapezoidal shape with cubic blends have been selected. For a given maximum acceleration and velocity, the trajectory parameters are chosen so as to achieve a minimum duration for each joint displacement. The corresponding joint forces and torques are reported in Fig. 7. On the basis of these plots, by considering a 100% security margins, the maximum force for joint 1 has been set to 2700 N, and the corresponding power is about 5 kW. For joint 2, the maximum torque has been set to 100 Nm and the corresponding power is 4 W. Finally, for joint 3, the maximum torque has been set to 320 Nm and the corresponding power is 120 W. The brushless motors can be selected on the basis of such values.

C. Batteries

The battery pack can be selected as follows. By considering a maximum cruise velocity of 60 km/h, the required maximum power is about 11 kW or, equivalently, the maximum force is 660 N. These values can be ensured thanks to

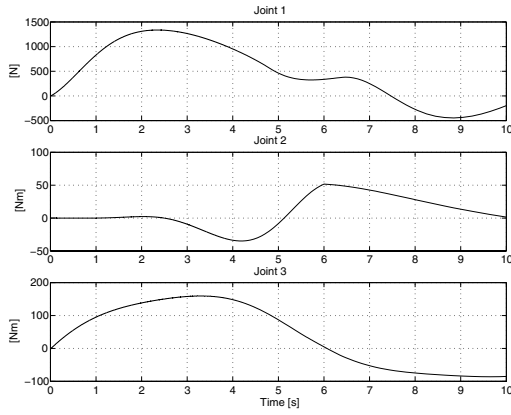


Fig. 7. Joint forces and torques.

the good aerodynamics features of the mechanical design. Considering that the motor is assumed to be controlled at constant maximum torque, it is possible to compute the capacity of the battery pack Q (measured in Ah) required to move the vehicle, in the form

$$Q = \frac{1}{3600} \frac{FS}{\eta e \nu} 2n \quad (1)$$

where S is the maximum distance from the place of the fire, n is the number of complete missions (where a mission is completed when the vehicle is back at the starting point), ν is the number of series elements of the battery pack with a voltage e , and $\eta < 1$ is the performance coefficient of the actuator. Assuming $S = 7000$ m, $n = 1$, $\nu = 18$, $e = 12$ V, $\eta = 0.9$, the corresponding capacity is $Q = 13.2$ Ah.

The choice of the batteries is a compromise between the maximum performance allowed by the most advanced technologies and the most common and convenient solutions available on the market. The most important requirements are reduced volume and weight, high energetic density, high capability to preserve energy, also after prolonged inactivity periods, and long cyclic duration.

Two different and significant options have been considered.

The first one is based on Pb batteries with nominal voltage of 12 V, capacity of 100 Ah with discharging time of 20 h, with density of energy of 100 Wh/dm³. On the basis of the required values of capacity and voltage of the battery pack, 18 batteries are necessary, providing a total energy of 21.6 kWh, with discharging time of about 6800 s, corresponding to about 7.7 missions of the robot. The total volume is 216 dm³ and the total weight is 540 Kg.

A more advanced option is based on Li-ion batteries with nominal voltage of 3.55 V, capacity of 45 Ah discharging time of 3 h, and density of energy 310 Wh/dm³. On the basis of the required values of capacity and voltage of the battery pack, 62 batteries are necessary, providing a total energy of 9.9 kWh, discharging time of about 2500 s, corresponding to about 3.5 missions of the robot. The advantage of these batteries is the small total volume, which

is 32 dm³ and the small total weight, which is 66 Kg, with a cyclic duration much higher than other kind of batteries.

V. CONCLUSIONS

The problem of prevention and fighting of fires in road and railways tunnels has been considered in this work. It has been recognized that technology and robotics may play a crucial role for preventing disasters in tunnels. A particular robotic system was presented, inspired by the ROBOGAT patent [5]. At the moment, the design of the mechanical part of the robot as well as the actuators and energy supply is in an advanced phase and some details are given in this work. Several problems still remain to be addressed or are under study. By the planning and control side, the most crucial aspects that have to be addressed to guarantee a minimal capability of operation of the system are: choice of suitable velocity and acceleration profiles so as to avoid slipping on the monorail and crabbing of the wheels; control of the connection between the telescopic hoses of the robot and the victaulic couplings of the pipe; control of the arm carrying the monitor and of the vehicle, both in autonomous operation and in teleoperation; supervision of all the information coming from the sensors on board and from those installed along the tunnel, as well as from the fault diagnosis system.

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