

Design Issues for a Fire-Fighting Robot on Tunnel Intervention

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Abstract—In this work a robot for fighting fires in road and railways tunnels is presented. The problem of safety in tunnels is first discussed with particular attention to the vulnerability to fire of actual tunnels, the potential disaster connected to non-controlled fires and the issues concerned with fire fighting in close environments as tunnels. The important role that robotics may play for fire fighting and disaster preventing is outlined and a particular robotic system, purposely designed for tunnels, is presented. A dynamic model of the robot is developed, which is exploited for dimensioning the mechanical structure and the actuators as well as for trajectory planning. The design takes into account the constraints deriving from mechanical and electrical charges, energy consumption, intervention time.



Fig. 1. Image of the Monte Bianco disaster.

I. INTRODUCTION

The problem of safety in road and railways tunnels and, in particular, the risk connected to fires has become of particular concern after the disasters in the Monte Bianco tunnel (connecting Italy to France, see Fig. 1) and in the Tauern tunnel (Austria) in 1999. The lesson learned is that the capability of intervention of the fire brigades in tunnels is very limited due to the extremely difficult 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 avoid that the fire becomes not controllable.

A recent report produced by the Inland Transport Committee of the United Nations Economic Commission for Europe (UNECE) [1] defines the minimal safety requirements for the tunnels of the Transport Europeans Network (TEN). Tunnels are very important infrastructures for the European Union and play a crucial role for the development of the regional economies [2]. On the other hand, most of the existing tunnels in Europe do not have adequate safety systems for the actual traffic volume, which is continuously increasing. For this reason, the risk of serious tunnel disasters, such as fires, is significantly increased during the last years and their costs are more and more relevant.

The last serious accidents on the TEN tunnels caused the loss of about 140 human lives (of which 39 in the Monte Bianco disaster and 12 in Tauern disaster). Moreover, the direct cost in terms of restoration expenses and the indirect costs deriving from the interruption of the service are considerable. Only for Italy, the direct costs amount to 210 million euros

per year, while the indirect costs amount to 450 million euros per year, during the last ten years [3].

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 gas, 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 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, purposely designed to guarantee a rapid intervention and continuous water restocking, is proposed. The system is based on the ROBOGAT patent [5], consisting on a self-cooling monorail vehicle, mounted on either the tunnel wall or ceiling, carrying a fire fighting monitor. The rail guarantees continuous water supply and the robot may be either teleoperated or autonomous, by using enhanced sensors as thermal and infrared cameras, pyrometers, gas chromatographs [6]. A dynamic model of the robot is developed, which is used for dimensioning the mechanical structure and the electrical actuators. Moreover, the problem of optimal trajectory planning in the presence of constraints deriving from mechanical and electrical charges, energy consumption, and intervention time is addressed.

II. STATE OF ART AND FUTURE PERSPECTIVES

The problem of tunnel safety must take into account the geometric characteristics (i.e., length, section, altimetric profile

and planimetric development, etc.) as well as the functional characteristics (number of tubes, number of ways, illumination, ventilation, traffic signs, visibility, etc.) of the tunnels [7]. The first element of risk in road tunnels is represented by the reduced visibility and safety distance taken by drivers; moreover, in case of accidents, the presence of other vehicles may facilitate propagation of flames. The intervention of fire brigades and fire-fighting devices may be difficult because of the distance of safety emplacements, the presence of traffic and other obstructions, the density of the smoke that reduces visibility. The risks to evaluate are also connected to the releasing of substances which may produce explosions, may be toxic or, in some cases, may be inflammable in the presence of water [8].

From the prevention point of view, different solutions have been adopted in the last years in European tunnels. 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 [9] and railways tunnels [10]. 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 [11]. 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 sensor, 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.

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 distributed along the tunnel, which is divided into sections; in case of detection of fire or high temperature smoke, the interested section is invaded by foam in order to facilitate the intervention of firemen [12].

It should be remarked, however, that the prevention and the fixed plants allows mitigating but not eliminating the crucial problems connected to fires in tunnels, i.e., access difficulty, difficult water supply, 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 may be composed by a fixed plant, as a monorail, used for robot locomotion and water supply, and a mobile part, composed by a vehicle moving on the monorail and a robotic arm carrying the fire fighting monitor. 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, for long tunnels, it could

be convenient to install more robots from booth sides or in intermediate positions, so that more robots may reach the fire place in shorter time.

The robot may be teleoperated from a remote control room or may perform some operation autonomously. Once the place of intervention is reached, the robot is innested to a fire hose and may drive the water jet to the fire. The fire hoses are suitably disposed along the monorail at a distance of about 30 m. Anyway, once connected to the water, the robot may slide in both senses along the monorail thanks to the adoption of telescopic tubes. A kinematic model of the robot can be found in [13].

The robot is equipped also with suitable sensors such as infrared video cameras, pyrometers, gas cromotographs, as well as control and data transmission hardware. More details about the robot structure and control are given in the following sections.

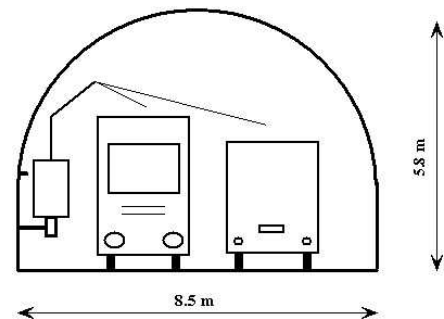


Fig. 2. A possible scenario for the robotic system.

III. SYSTEM REQUIREMENTS

The main problems to be solved for the proposed robotic system are those typical of the service and rescue robots that have to execute important and complex operations in remote environments without the possibility of continuous energy supply. These problems can be identified as:

- choice and dimensioning of a locomotion system able to transport the robot on the intervention site;
- choice and dimensioning of the kinematic structure and of the actuators.

The objectives to be satisfied are:

- the duration of each operation cannot be greater than specified values;
- the requested energy has to be minimal;
- the efforts on the kinematic structure and on the vehicle must be kept into security margins.

The main operations that have to be made automatic are:

- monitoring of the environment;
- guidance of the robot to the location of the fire;
- optimal positioning of the robot for the required task;
- actuation of the fire-fighting monitor and of the water valves.

The design of the robot and of the corresponding controller requires the definition of the possible intervention scenarios. A typical scenario is that represented in Fig. 2, where the robot is placed on the side of tunnel; in different configurations, the robot may be mounted on the ceiling.

IV. MODELLING

A. Robotic structure

The kinematic structure of the robot can be described in terms of a prismatic joint (joint variable q_1), corresponding to a mobile base sliding on a rail, three rotational joints (joints variables q_2, q_3, q_4), corresponding to an anthropomorphic structure [14], and one terminal rotational joint (joint variable q_5), corresponding to the yaw motion of the end-effector, i.e., the fire-fighting pistol. The axes of the last two joints intersect in a point. A sketch of the kinematic structure can be seen in Fig. 3.

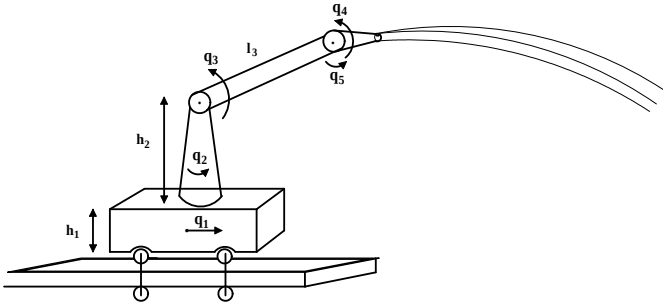


Fig. 3. Sketch of the robotic structure.

The position and orientation of the tip, with respect to a reference frame fixed to the rail, can be characterized in terms of the position coordinates x, y, z and of the angles φ_e and φ_l , corresponding to the end-effector pitch and yaw angles. These quantities can be computed as:

$$\begin{aligned} x &= q_1 + l_3 c_2 c_3 \\ y &= l_3 s_2 c_3 \\ z &= h_1 + h_2 + l_3 s_3 \\ \varphi_e &= q_3 + q_4 \\ \varphi_l &= q_2 + q_5 \end{aligned}$$

where $h_1 = h_2 = l_3 = 1$ m, and s_i, c_i denote $\sin(q_i)$ and $\cos(q_i)$ respectively, $i = 1, \dots, 5$.

By using the Lagrange formulation, the dynamic model can be written in terms of the (5×1) joint vector $\mathbf{q}$ in the form:

$$\mathbf{B}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{k}(\dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) = \boldsymbol{\tau} - \mathbf{J}^T(\mathbf{q})\mathbf{d} \quad (1)$$

where $\mathbf{B}$ is the (5×5) inertia matrix, $\mathbf{c}$ is the (5×1) vector of the Coriolis and centrifugal generalized forces, $\mathbf{k}$ is the (5×1) vector of friction, $\mathbf{g}$ is the (5×1) vector of gravitational forces, $\boldsymbol{\tau}$ is the (5×1) vector of the generalized actuator forces, $\mathbf{J}(\mathbf{q})$ is the (3×5) geometric Jacobian of the robot, and $\mathbf{d}$ is the (3×1) vector of the reaction forces of the water jet. Notice that the above dynamic model takes into account only the dynamic

contribution of the first three links, while that of the last link (i.e., the fire fighting pistol) has been neglected. On the other hand, the dynamic effects of the reaction force $\mathbf{d}$ of the water jet shoot by the pistol have been explicitly considered.

The analytic expressions of the various terms are:

$$\mathbf{B}(\mathbf{q}) = \begin{bmatrix} m & as_2c_3 & ac_2s_3 \\ as_2c_3 & I_2 + I_3c_3^2 & 0 \\ ac_2s_3 & 0 & I_3 \end{bmatrix},$$

$$\mathbf{c} = \begin{bmatrix} ac_2c_3(\dot{q}_2^2 + \dot{q}_3^2) - 2as_2s_3\dot{q}_2\dot{q}_3 \\ 0 \\ I_3c_3s_3\dot{q}_2^2 \end{bmatrix},$$

$$\mathbf{k} = \begin{bmatrix} r_0 + k_1\dot{q}_1 + k'_1\dot{q}_1^2 \text{sgn}\dot{q}_1 \\ k_2\dot{q}_2 \\ k_3\dot{q}_3 \end{bmatrix},$$

$$\mathbf{g}(\mathbf{q}) = \begin{bmatrix} r_0 \\ 0 \\ gac_3 \end{bmatrix},$$

$$\mathbf{J}^T(\mathbf{q})\mathbf{s} = \mathbf{d} \begin{bmatrix} c_{34}c_{25} \\ l_3c_3s_5 \\ l_3s_4 \end{bmatrix},$$

where m is the total mass of the robotic system, m_i represents the mass of the link i ($i = 1, 2, 3$), $a = m_3l_{C3}$, where l_{C3} is the distance of the center of mass of the link 3 with respect to the joint 3 axis, I_i is the inertia moment of the link i with respect to corresponding joint rotation axis, k_i is the friction coefficient for the joint i ($i = 1, 2, 3$), $g = 9.8 \text{ m/s}^2$ is the gravity acceleration, and r_0 is a constant that takes into account the gravitational effect of the slope of the tunnel. For the mobile base, a rolling friction coefficient k'_1 has been also considered. Moreover, s_{ij} and c_{ij} denote $\sin(q_i + q_j)$ and $\cos(q_i + q_j)$ respectively, $i, j = 1, 2, 3$. Finally, the vector $\mathbf{d}$ has been assumed of magnitude d and directed along an axis aligned to the axis of fire fighting pistol.

The values chosen for the dynamic parameters are: $m = 1500$ kg, $m_1 = 1470$ kg, $m_2 = m_3 = 15$ kg, $a = 1$ kg m, $I_2 = 6 \cdot 10^{-3} \text{ kg m}^2$, $I_3 = 5 \text{ kg m}^2$, $r_0 = 300$ N, $k_1 = 20 \text{ N s m}^{-1}$, $k_2 = k_3 = 10 \text{ N s m}^{-1}$, $k'_1 = 3 \text{ N s}^2 \text{ m}^{-2}$.

B. Actuators

The robot actuators are chosen as brushless motors for the manipulator, while two three-phase asynchronous motors are used 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 the hypothesis that the PWM frequency is sufficiently high, it can be assumed that all the electrical quantities have a sinusoidal regime, by neglecting the transient regime. Hence, the motor torque C

and the effective value of the current I can be computed respectively as [15]:

$$C = \frac{3p}{2\pi f} \left(\frac{V}{m} \right)^2 \frac{R}{R^2/s + sX^2} \quad (2)$$

$$I = \frac{V/m}{\sqrt{(R/s)^2 + X^2}} \quad (3)$$

where V is the effective value of the input voltage of the motor (i.e., the star connection voltage of the equivalent three-phase power supply provided by the inverter), f is the corresponding frequency, ω is the angular velocity of the rotor, p is the number of poles of the stator, m is the transformation ratio of the equivalent electrical model, R is the equivalent resistance, $X = 2\pi fL$ is the reactance of the equivalent dispersion inductance L , and $s = (2\pi f - p\omega)/2\pi f$ is the motor slip. Finally, the maximum value of the torque, achieved when the slip value is $s = R/X$, is

$$C_{max} = \frac{3p}{2m^2L_2} \left(\frac{V}{2\pi f} \right)^2.$$

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

V. MODEL-BASED DESIGN

A. Asynchronous motors dimensioning

The dynamic model of the robot derived above and the relations written for the asynchronous motors can be used for dimensioning the actuators and batteries and for the optimal selection of the robot trajectories.

For dimensioning the asynchronous 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 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.

The maximum force required of the asynchronous motors can be computed by considering the first equation of the model (1) and neglecting the Coriolis and centrifugal forces, i.e.:

$$m\ddot{q}_1 + r_0 + k_1\dot{q}_1 + k'_1\dot{q}_1^2 \text{sgn}\dot{q}_1 = \tau_1; \quad (4)$$

assuming that the velocity is constant and equal to v_M , the corresponding maximum force is

$$F = r_0 + k_1v_M + k'_1v_M^2. \quad (5)$$

The corresponding mechanical power is

$$\hat{P} = (r_0 + k_1v_M + k'_1v_M^2)v_M. \quad (6)$$

For the numerical value of v_M computed above, the maximum force is about $F = 2400 \text{ N}$, while the corresponding power is $\hat{P} = 40 \text{ kW}$.

Assuming that the motor is 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

$$Q = \frac{1}{3600} \frac{FS}{e\nu} 2n \quad (7)$$

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), and ν is the number of series elements of the battery pack with a voltage e . Assuming $S = 7000 \text{ m}$, $n = 1$, $\nu = 18$, $e = 12 \text{ V}$, the corresponding capacity is $Q = 43.2 \text{ Ah}$.

To the aim of choosing the vehicle trajectory, it is useful to compute the limit velocity and acceleration profiles in the hypothesis that the motors are controlled with constant maximum torque. The velocity and acceleration profile $v(t)$ and $\dot{v}(t)$ can be computed by integrating the differential equation (4) with initial condition $v(0) = 0$, assuming $\tau_1 = F$. With the given numerical data, the corresponding time histories are represented in Fig. 4. Notice that the maximum acceleration is lower than the maximum value required to avoid slipping.

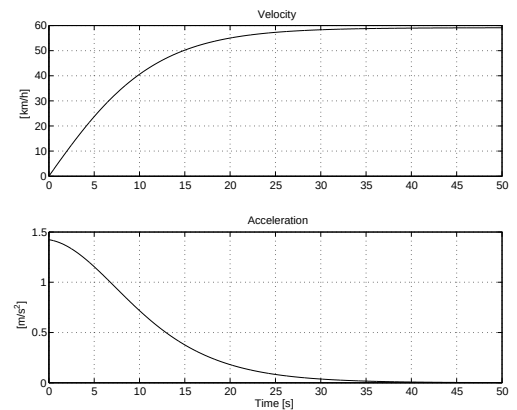


Fig. 4. Profile of maximum velocity (top) and acceleration (bottom).

A convenient choice of the robot 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. 4, 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 trajectory duration Δ can be computed.

To reduce the energy requirements, a higher value Δ_d of the trajectory duration can be set, by introducing a suitable scaling factor $r > 1$, i.e.,

$$\Delta_d = r\Delta$$

The corresponding scaled velocity takes the form

$$v_d(t) = \frac{1}{r}v\left(\frac{t}{r}\right) \quad t \in [0, \Delta_d]$$

being $v(t)$ the velocity trajectory corresponding to the duration Δ . Hence, the scaled maximum velocity and acceleration are respectively $v_{Md} = v_M/r$ and $a_{Md} = a_M/r^2$. The curve representing the energy consumption as a function of the duration of the trajectory for a fixed distance of 7 km is reported in Fig. 5.

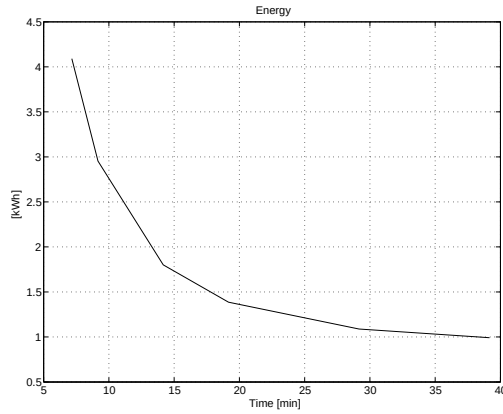


Fig. 5. Energy consumption with respect to the duration of the trajectory.

A minimum time trajectory can be chosen according to the formulation reported in Appendix, i.e., using a velocity profile of pseudo-trapezoidal shape with cubic blends, and adopting the design methodology reported above. The corresponding trajectory in terms of time history of velocity, power and torque, is reported in Fig. 6. It can be seen that all the quantities (maximum velocity, maximum power and maximum force) satisfy the design constraints.

B. Brushless motors dimensioning

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). To this aim, the dynamic model developed in Section IV can be conveniently exploited, at least for the dimensioning of the motors of the first two joints of the manipulator (joints 2 and 3). The choice of the motors of the last two joints (joints 4 and 5) can be made on the basis of torque requirements, due to the water jet thrust, that can be computed separately.

The selected manoeuvre corresponds to a situation where the mobile base (joint 1) has to advance by 10 m in the forward

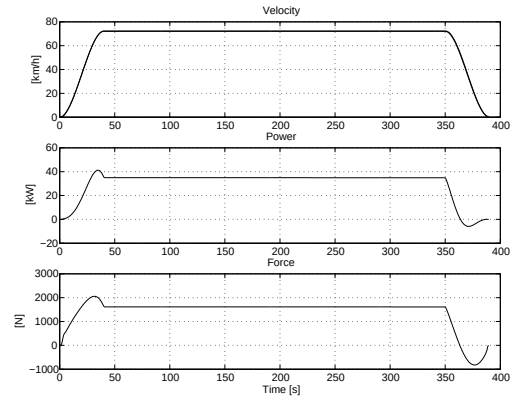


Fig. 6. Time histories of the velocity (top), power (center) and force for a minimum time trajectory.

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 mathematical details are given in the Appendix. As an example, in Fig. 7 the position, velocity and acceleration trajectories for the joint 3 are reported. In this case, the maximum velocity and acceleration have been set to 0.37 rad/s and 0.1 rad/s², and the corresponding minimum duration is 11.9 s. Moreover, a value of 150 N has been considered for the maximum value of the water jet thrust, assuming that the angles φ_e and φ_j move according to sinusoidal trajectories of amplitude $\pi/6$ and frequencies 0.1 Hz and 0.2 Hz, respectively. To consider a realistic situation, the thrust has been assumed as the step response of a first-order system with time constant $\tau = 1$ s.

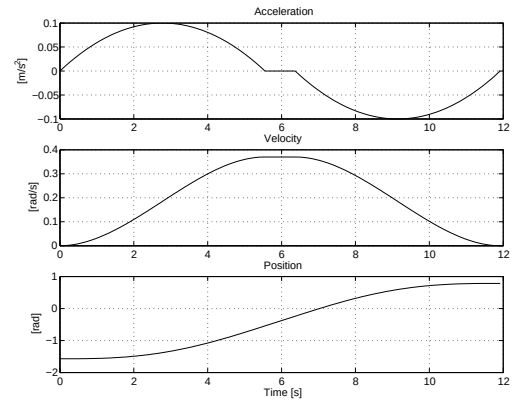


Fig. 7. Acceleration (top), velocity (medium), and position (bottom) trajectory for joint 3.

The corresponding joint forces and torques are reported in Fig. 8. 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; these values are compatible with those considered in the previous

subsection. 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.

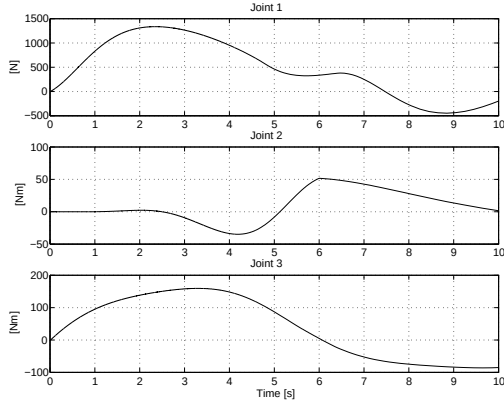


Fig. 8. Joint forces and torques.

The dynamic model can be also used for tuning the motion controllers. For the considered application, simple independent joint controllers can be adopted, such as PID controllers, or PD controllers with gravity compensation.

VI. APPENDIX

The joint trajectory has been set with a velocity profile of pseudo-trapezoidal shape with cubic blends. An example of trajectory profile was reported in Fig. 7. This choice allows setting the maximum velocity v_M and acceleration a_M of the trajectory in a simple way; moreover, the acceleration profile is a continuous function; finally, the maximum acceleration and velocity are not required in the same time.

The positive acceleration profile has the expression

$$a(t) = a_M \left(-\frac{4}{T_a^2} t^2 + \frac{4}{T_a} t \right) \quad t \in [0, T_a]$$

where T_a is the so-called acceleration time, i.e., the time interval with positive (or negative) acceleration. Hence, the maximum velocity can be computed by solving the integral

$$v_M = \int_0^{T_a} a(\tau) d\tau = \frac{2}{3} T_a a_M.$$

Thus, for a given value of v_M , a_M , the acceleration time T_a can be computed as

$$T_a = \frac{2}{3} \frac{v_M}{a_M};$$

the corresponding displacement at time T_a can be computed as

$$s_a = s(T_a) = \int_0^{T_a} v(\tau) d\tau = \frac{3}{4} \frac{v_M^2}{a_M}.$$

At this point, in the case the total position displacement satisfy the inequality $s \geq 2s_a$, after the time T_a , the velocity

becomes constant for a time T_c that can be computed as

$$T_c = \frac{s - 2s_a}{v_M}.$$

Hence, the total trajectory duration T_m can be computed as

$$T_m = 2T_a + T_c = 3 \frac{v_M}{a_M} + \frac{1}{v_M} \left(s - \frac{3}{2} \frac{v_M^2}{a_M} \right).$$

This time is the minimum time that can be achieved with the assigned maximum velocity and acceleration.

In the case that $s < 2s_a$, only the maximum acceleration a_M can be assigned, while the maximum velocity can be decreased to a value $v'_M < v_M$ so that, for the corresponding $T'_a < T_a$, the equality $s = 2s(T'_a)$ is satisfied. This value is

$$v'_M = \sqrt{\frac{2}{3} a_M s}.$$

The minimum time can be computed as

$$T_m = 2T'_a = \sqrt{\frac{6s}{a_M}}.$$

VII. CONCLUSION

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]. A dynamic model of the robot has been developed, as well as a dimensioning procedure for robot actuators, which takes into account the constraints deriving from mechanical and electrical charges, energy consumption, and intervention time.

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