Two multi-sensor-based control strategies for driving a robot amidst obstacles

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Abstract: We present two sensor-based control strategies for driving a wheeled robot equipped with a mobile camera and a 2D laser range finder amidst obstacles. The goal of the work is to show that a feedback control can be designed on the base of the information coming from different sensors considered at the same level. Taking advantage from the redundancy with respect to the nominal visual task the controller allows to modify the robot trajectory to avoid obstacles. In both cases, the control stability and the consistency of the method is proven. Simulations results are described at the end of the paper.

1 Introduction

Sensor-based control allows to define the robot motion by regulating data emanating from the perception of specific landmarks of the scene. Among these techniques, visual servoing relies on the regulation to zero of the error between what the robot really sees and what it must see when the task is perfectly performed [1]. By fixing the camera on a platform or an arm to allow it to move independently from the base, it has been shown that the method can be applied to control nonholonomic mobile robots [3]. Visual servoing is particularly well suited for executing positioning or tracking tasks with respect to a target. However, even if sensors like vision provides a very rich information, performing a complex navigation task requires to consider more than one kind of data. For instance, a tracking task amidst obstacles requires to take into account visual and proximetric data at the same time. To answer this problem, we have proposed several strategies allowing to mix the visual information with proximetric data to execute a tracking task [5] [6]. In these works, the robot was not redundant with respect to the nominal task, and it was necessary to switch to another control law for driving the base near the obstacles. The goal of this paper is to show that under certain hypotheses it is possible to design a generic controller to drive the robot both far and close to the obstacle. The method takes advantage from the system redundancy with respect to the nominal visual task to perform simultaneously obstacle avoidance and target tracking. We show that redundancy can be introduced either by defining a low dimensioned vision based task, or by increasing the mobility of the mechanical structure of the robot.

2 Description of the robot

The robot is a hand-eye system which consists of a mobile base equipped with a camera mounted on a 6 dof-arm (figure 1). Our objective is to elaborate different control strategies to position the camera in front of a fixed target and avoid stationary obstacles. To avoid target occlusions, the obstacles are supposed to be smaller than the target. We denote by $[x\ y\ \theta]^T$ a configuration of the mobile base with respect to the world frame $\mathcal{F}$. D_x represents the distance between M and O_0, while $\mathcal{F}_M(M, x_M, y_M, z_M)$ and $\mathcal{F}_C(C, x_C, y_C, z_C)$ are two frames respectively linked to the robot and the camera. As the target height is supposed to be equal to the camera optical center height, planar movements suffice to perform our visual task. The 6 dof-arm is fixed in a configuration which simulates a planar manipulator (see figure 2).

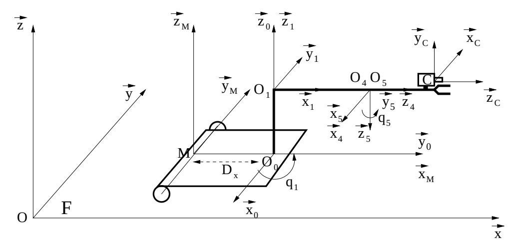

Figure 1: Mobile base with a manipulator arm

In this work, only the first and fifth joints q_1 and q_5 of the arm will be controlled. We denote by $\mathcal{F}_i(O_i, x_i, y_i, z_i)$ the frames attached to each link of the arm (see figure 2), q_1 and q_5 are respectively defined by the oriented angles (x_0, x_1) and (x_4, x_5) about z_0 and

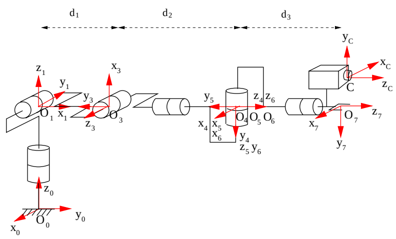

Figure 2: A configuration of the arm

z_4. The control input of the whole mechanical system is defined $\dot{q} = [v\ \omega\ \dot{q}_1\ \dot{q}_5]^T$, where v and ω are the linear and the angular velocities of the cart. The state vector $q = [s_c\ \theta\ q_1\ q_5]^T$ (s_c representing the curvilinear abscissa of the reference point M of the robot). Let $T^c = [V^c_{\mathcal{F}_C/\mathcal{F}}, \Omega^c_{\mathcal{F}_C/\mathcal{F}}]^T$ be the kinematic screw representing the translational and rotational velocity of $\mathcal{F}_C$ with respect to $\mathcal{F}$, expressed in $\mathcal{F}_C$. The kinematic screw is related to the joint velocity vector by the robot jacobian matrix J. As the camera is constrained to move horizontally, it is sufficient to consider a reduced kinematic screw $T^c_{\text{red}} = [V_{x_c}, V_{z_c}, \Omega_{y_c}]^T$, and a reduced jacobian matrix J_{arm}:

$$J_{\text{arm}} = \begin{pmatrix} \cos(q_1 - q_5) & \alpha_4 & \alpha_5 & \alpha_6 \\ \sin(q_1 - q_5) & \alpha_7 & \alpha_8 & \alpha_9 \\ 0 & 1 & 1 & -1 \end{pmatrix} \tag{1}$$

Coefficients α_i are defined as follows:

$$\begin{aligned}
\alpha_4 &= (D_x + \alpha_2)\sin(q_1 - q_5) + \alpha_1\cos(q_1 - q_5) + (d_1 + d_2)\cos q_5, \\
\alpha_5 &= (d_1 + d_2)\cos q_5 + \alpha_1\cos(q_1 - q_5) + \alpha_2\sin(q_1 - q_5), \\
\alpha_6 &= -\alpha_2\sin(q_1 - q_5) - \alpha_1\cos(q_1 - q_5), \\
\alpha_7 &= -(D_x + \alpha_2)\cos(q_1 - q_5) + \alpha_1\sin(q_1 - q_5) - (d_1 + d_2)\sin q_5, \\
\alpha_8 &= -(d_1 + d_2)\sin q_5 + \alpha_1\sin(q_1 - q_5) - \alpha_2\cos(q_1 - q_5), \\
\alpha_9 &= \alpha_2\cos(q_1 - q_5) - \alpha_1\sin(q_1 - q_5).
\end{aligned}$$

α_1 and α_2 represent the coordinates of O_6C in $\mathcal{F}_0$, while distances d_i are defined as in figure 2. As J_{arm} is a 3×4 matrix, the three degrees of freedom of the camera are controlled by four actuators. The robot is therefore redundant with respect to the positioning of $\mathcal{F}_C$.

As previously mentioned, in addition to the CCD camera, the robot is equipped with a 2D laser rangefinder. On the base of the laser signal we compute a set of data (d, α, χ) characterizing the closest obstacle. d is the signed distance between the robot reference point M and the closest point Q on the obstacle, α is the angle between the tangent $\vec{\tau}$ to the obstacle at Q and the robot direction $\vec{x}_M$, and χ is an estimation of the curvature at Q (see figure 3). For the problem to be well stated, the distance between two obstacles is supposed to be greater than $2d_+$. This allows to consider each obstacle independantly.

3 Visual servoing and redundancy

We consider the visual servoing technique introduced in [1] which relies on the task function formalism [7]. The task is defined by the regulation of a task function e to zero. A sufficient condition for the control problem to be well-conditioned is that e is ρ-admissible. A necessary condition for this property to be verified is that the task jacobian matrix $\partial e/\partial q^T$ is regular around the ideal trajectory q_r which correspond to $e = 0$ (see [7]). The target is made of four points whose coordinates (X_i, Y_i) $(i = 1 \ldots 4)$ define an 8-dimensioned vector of visual signals s in the camera plane. At each configuration of the robot, the variation of the signals is related to the kinematic screw T^c_{red} by means of the 8×3 interaction matrix L_{red}: $\dot{s} = L_{\text{red}}\, T^c_{\text{red}}$ where L_{red} is given by the optic flow equations [1].

Consider the following task function $e(q(t))$:

$$e(q(t)) = C\epsilon \text{ with } (s(q(t)) - s^*) \tag{2}$$

s^* is the value of the visual signals corresponding to the realization of the task. As the target is fixed, s depends only on $q(t)$. C is a constant, full rank, 3×8 matrix which allows to take into account more visual features than available degrees of freedom. As it depends on 3D information which are difficult to estimate on line, L_{red} will be taken constant and equal to its value when $s = s^*$ during the whole task execution as in [1]. In this case, L_{red} can be proven to be of full rank 3. Therefore, a positioning task constrains the three degrees of freedom of the camera defined by T^c_{red}. As $\partial e/\partial q^T = CL_{\text{red}}J_{\text{arm}}$ is a 8×4 matrix, e is not a ρ-admissible task function. As four actuators control three degrees of freedom of the camera, the robot is redundant with respect to the positioning task. An infinity of ideal trajectories q_r correspond to the regulation of e to zero. Further constraints have to be introduced to define the motion in a unique way.

4 Redundancy from the vision-based task

This strategy is based on the definition of a low-dimensioned vision-based task to make possible the simultaneous execution of the tracking and the avoidance movement in the vicinity of an obstacle. The vision task will be simply defined as orientating the camera towards the target. We reduce the previous system reduce to a pan-platform. We fix the fifth joint q_5 to zero and control only q_1. q and $\dot{q}$ are then reduced to $[s_c\ \theta\ q_1]^T$ and $[v\ \omega\ \dot{q}_1]^T$. The corresponding jacobian J_{pl} is obtained from 1 by suppressing the fourth column of J_{arm} and setting q_5 to zero in the expressions of α_i. In this case, J_{pl} is a 3×3 matrix. The vision-based task is defined by the following one dimensional task function:

$$e_1 = l^T \epsilon \tag{3}$$

where $l^T = 1/4\ [0\ 1\ 0\ 1\ 0\ 1\ 0\ 1]$. This task function represents the ordinate of the error between the projection of the center of gravity of the target when the camera is at the desired position and when it is far from it. Classically, the control input is deduced from the exponential decay of a ρ-admissible task function [1] [5] [6]. We have chosen to define only ω and $\dot{q}_1$ from sensory data regulation, while the robot linear velocity v is determined at another level of control. We define a reduced control vector $\dot{q}' = [\omega\ \dot{q}_1]^T$, while the linear velocity will be specified as follows: when the robot is in the free space, v is regulated to its maximal value after an acceleration phase; in the vicinity of the obstacles, v is reduced to a security value v_{sec} allowing to pass round the obstacle without saturating. With the external definition of v and the choice of e_1, two degrees of freedom out of three are fixed. The way to fix the remaining degree of freedom will depend on the distance to the closest obstacle.

Phase 1: Far from the obstacles: v is fixed to $v_{\max}$. As the regulation of e_1 constrains the camera to face the target, the idea is to make the base move in this direction. We impose the linear velocity v_1 of the first joint center of rotation O_1 to be directed along the x_1-axis. Let $\varphi = q_1 - \pi/2$ be the angle between vectors x_M and x_1. As $v = v_1 \cos(\varphi)$, we get:

$$\omega = \frac{v}{D_x}\tan(\varphi) \qquad (4)$$

This definition of ω requires $|\varphi|$ to be strictly smaller than $\frac{\pi}{2}$. A simple way to avoid this singularity is to constrain the motion of O_1 progressively: at the beginning of the task v_1 is orientated along the bisector of φ, then its direction is continuously modified to become rapidly tangent to the x-axis. Introducing $\bar{\varphi} = (1 - e^{-t}/2)\varphi$ and $K_2 = l^T L_{\text{red}} J_{\text{pl}}$, the motion is defined by:

$$\begin{cases} \dot{e}_2 = K_2^T \dot{q} = K_2^T [0\ \ \dot{q}'^T]^T + K_2^T [v\ \ 0\ \ 0]^T \\ \omega = \frac{v}{D_x}\tan\bar{\varphi} \end{cases}$$

Introducing:

$$A = \begin{pmatrix} K_2^T \\ 0\ 1\ 0 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad (5)$$

and

$$a_1 = \begin{pmatrix} -\lambda_2 e_1 \\ \frac{v}{D_x}\tan\bar{\varphi} \end{pmatrix} - \begin{pmatrix} K_2^T \\ 0\ 1\ 0 \end{pmatrix} \begin{pmatrix} v \\ 0 \\ 0 \end{pmatrix} \qquad (6)$$

and, assuming that A is invertible[1], the reduced control vector $\dot{q}' = [\omega\ \dot{q}_1]^T$ is expressed by:

$$\dot{q}' = A^{-1} a_1 \qquad (7)$$

[1] A direct computation of $\det(A)$ shows that A is always invertible if the sum of the ordinates of the four points $\sum_{i=1}^{4} Y_i$ is not too large. This is always the case for our problem as the projected target remains well centered in the image plane.

Phase 2: Close to the obstacles: We define three envelopes ξ_+, ξ_0, ξ_- respectively located at d_+, d_0, d_- from the obstacles (figure 3).

Remark 1 *The direction to pass round the obstacle is determined by the orientation of the robot with respect to the obstacle when it is detected ($d \leq d_+$). The direction of the unit vector $\vec{\tau}$ is chosen such that the angle α between $\vec{x}_M$ and $\vec{\tau}$ belongs to $[-\pi/2, \pi/2]$.*

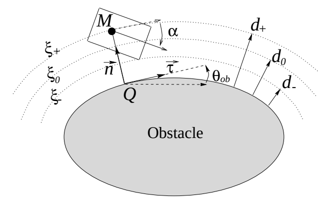

Figure 3: Mobile frame and envelops

As soon as the robot enters the zone delimited by ξ_+ the linear velocity is continuously reduced by the external loop (as a function of d) to reach the security value v_{sec} on ξ_-. On the other hand, as soon as $d \leq d_-$ the constraint on the angular velocity of the base is modified. $\dot{q}'$ is determined such that v_1 be directed along $\vec{\tau}$. As before, we introduce a short transition phase to smooth the motion and avoid the singularity $\alpha = \pi/2$ by constraining O_1 to move along the direction defined[2] by $\bar{\alpha} = \alpha(1 - e^{-(t-t_0)}/2)$. Defining

$$a_2 = \begin{pmatrix} -\lambda_2 e_1 \\ \frac{v}{D_x}\tan\bar{\alpha} \end{pmatrix} - \begin{pmatrix} K_2^T \\ 0\ 1\ 0 \end{pmatrix} \begin{pmatrix} v \\ 0 \\ 0 \end{pmatrix}$$

and assuming A invertible, defined as before by (5), the solution is given by:

$$\dot{q}' = A^{-1} a_2 \qquad (8)$$

Control strategy: To design a global controller allowing to commute smoothly from one phase to the other, we use a convex combination of (7) and (8) as in [5] [6]. We define:

$$\dot{q} = (1 - \mu(d))\dot{q}_{\text{VS}} + \mu(d)\dot{q}_{\text{AV}} \qquad (9)$$

$\dot{q}_{\text{VS}}$ and $\dot{q}_{\text{AV}}$ are the visual servoing and avoidance control laws, and $\mu(d)$ is a three order polynomial in d. $\mu(d) = 0$ so long as $d > d_0$ and varies continuously from 0 to 1 between ξ_0 and ξ_-; $\mu(d) = 1$ when $d < d^-$. The avoidance phase ends when the camera becomes tangent the main axis of the base ($q_1 = \pi/2$).

5 Redundancy from the mechanical structure

We consider now the model of represented of figure 1 without constraint on q_5. The tracking task is now

[2] t_0 is the time at which the avoidance phase starts.

defined by (2), and the robot becomes redundant with respect to it. Considering that the camera positioning and the obstacle avoidance share the same priority, we define two primary objectives: the first one realizing the sole vision based task in the free space, the second performing both tracking and obstacle avoidance when necessary. The control strategy requires to switch from one objective to the other depending on the distance to the obstacle. However, here, the control law is designed by mixing these objectives at the task level and not at the control level as in section 4.

Phase 1: Far from the obstacles: We consider the following task function e_{VS}:

$$e_{\text{VS}} = \begin{pmatrix} e^T & q_5 - q_5^* \end{pmatrix}^T \quad (10)$$

where q_5^* represent the desired configuration of the fifth joint. Its jacobian matrix $J_{\text{VS}} = \partial e_{\text{VS}} / \partial q^T$ is:

$$J_{\text{VS}} = \begin{pmatrix} C L_{\text{red}} J_{\text{arm}} \\ J_{q_5} \end{pmatrix} \text{ where } J_{q_5} = [0\ 0\ 0\ 1] \quad (11)$$

As J_{VS} is always regular[3], e_{VS} is always ρ-admissible. It allows[4] to realize both the positioning of the camera and the regulation of q_5 to q_5^*.

Phase 2: Close to the obstacles: The strategy consists of making the robot follow a security envelope ξ_0. We consider the following task function:

$$e_{\text{AV}} = \begin{pmatrix} e^T & d - d_0 \end{pmatrix}^T \quad (12)$$

d represents the distance between the robot and the obstacle. Nonetheless, this distance cannot be described as the distance between M and Q as in figure 3. Indeed, as $\dot{d} = v \sin\alpha$, the task jacobian J_{AV} would not be of full rank when $\alpha = 0$, and the task no more ρ-admissible. This problem is mainly related to the nonholonomic constraint of the base. To overcome it, it suffices to define d as the distance between any holonomic point of the base (for example, O_0) and the closest point on the obstacle. J_{AV} is given by:

$$J_{\text{AV}} = \begin{pmatrix} C L_{\text{red}} J_{\text{arm}} \\ J_d \end{pmatrix} \quad (13)$$

where $J_d = [\sin\alpha\ \ -D_x \cos\alpha\ 0\ 0]$. J_{AV} presents a singularity when $\sin(q_1 + \alpha) = 0$, that is when the arm becomes perpendicular to the envelope during the avoidance phase. In this case, it is physically impossible to perform *simultaneously* the tracking and the avoidance. It is necessary to stop executing the positioning task while avoiding the obstacle as it is done in [5] [6] or [10] for instance.

[3] $\det(J_{\text{VS}}) = -D_x$

[4] We are not interested in this paper to use at best the redundancy of the robot in the free space. Our objective is just to define two global ρ-admissible tasks to mix them consistently at the task level.

Control synthesis: The method relies on the mixing of e_{VS} and e_{AV} at the task level. It consists of defining a global task e' and design a controller to make it decrease to zero. We define:

$$e' = (1 - \mu(d)) e_{\text{VS}} + \mu(d) e_{\text{AV}} \quad (14)$$

e_{VS} and e_{AV} are defined by (10) and (12) and $\mu \in [0, 1]$ is a scalar function depending on d.

Far from the obstacles ($d > d_0$), μ is fixed to zero and only e_{VS} is considered. On the contrary, close to it ($d < d_0$), μ jumps to 1, and e_{AV} is realized. The passing-round sense is the one along which both e and $d - d_0$ decrease. To avoid discontinuities in the final control law, we introduce a second envelope ξ_+ surrounding the obstacle at a constant distance $d_+ = d_0 + \varepsilon$. Between ξ_0 and ξ_+, μ varies continuously from 0 to 1 as a three order polynomial in d. To design the controller we impose an exponential decrease of e' to zero.

$$\dot{q} = -\lambda J_T^{-1} e' \text{ with } \lambda > 0 \quad (15)$$

$J_T = (1 - \mu) J_{\text{VS}} + \mu J_{\text{AV}} + (e_{\text{AV}} - e_{\text{VS}}) J_\mu$ with $J_\mu = \partial\mu / \partial q^T$. Note that the final control law involves the derivative of μ which must be itself continuous.

Remark 2 *When $\mu \in]0, 1[$, the expression of J_T and $\det(J_T)$ become complex and it is difficult to establish the ρ-admissibility of e'. Nonetheless, as $d - d_0$ vanishes very quickly, μ tends to 1 rapidly. Then, if ε is chosen sufficiently small, the ρ-admissibility property may be conserved, unless the arm becomes perpendicular to ξ_0.*

The control law (15) allows to guarantee the task feasability. Actuators saturation can be avoided by choosing λ sufficiently small. Moreover, the exponential decrease of d towards d_0 insures non collision as d remain greater than d_0. As the positioning task is performed even during the obstacle avoidance, the target cannot be lost. The main limitation of this approach comes from the fact that the camera is constrained to move on a "virtual rail" perpendicular to the target and passing through the center of it. The avoidance motions are then limited by the length of the arm. The redundant task formalism [7] could appear to be a way to overcome this limitation. However, we have applied this approach to our problem without getting a satisfactory result. This last approach is summerized in the next paragraph.

The use of task redundancy formalism: The problem is stated in terms of minimizing a cost function to obtain the best execution of a secondary objective while executing the nominal task. This technique has been already used to execute a vision based task while following a trajectory [1] [8] or avoiding joint limits or singularities [9] [2]. As obstacle avoidance cannot be considered as secondary we define two different global tasks valid, either in the free space or near the obstacles. We consider the two criteria $h_{\text{VS}} = \frac{1}{2}\left(q_{bras} - q^*_{arm}\right)^T \left(q_{arm} - q^*_{arm}\right)$ and $h_{\text{AV}} = \frac{1}{2}\epsilon^T\epsilon$, where $q_{arm} = [q_1\ q_5]^T$ and $q^*_{arm} = [q^*_1\ q^*_5]^T$. h_{VS} and h_{AV} are respectively the costs to be minimized far and near the obstacles. The first one, valid in the free space, guarantees the avoidance of joint limits [9] [2], while the second one allows to track the target while passing-round the obstacle. As the positioning task and the avoidance are the nominal tasks to be realized far and near the obstacles, we define the corresponding primary objectives by e and $e_d = d - d_0$. Following the task function formalism, the two global tasks e_{VS} and e_{AV} corresponding to the constrained minimization of h_{VS} and h_{AV} are given by:

$$\begin{array}{l} e_{\text{VS}} = W^+_{\text{VS}} e + \beta_{\text{VS}}(I - W^+_{\text{VS}} W_{\text{VS}}) g_{\text{VS}},\ \beta_{\text{VS}} > 0 \\ e_{\text{AV}} = W^+_{\text{AV}} e_d + \beta_{\text{AV}}(I - W^+_{\text{AV}} W_{\text{AV}}) g_{\text{AV}},\ \beta_{\text{AV}} > 0 \end{array} \quad (16)$$

where $g_{\text{VS}} = [0\ 0\ q_{arm} - q^*_{arm}]^T$ and $g_{\text{AV}} = J^T_{\text{arm}} L^T_{\text{red}} \epsilon$ are the gradients of h_{VS} and h_{AV} with respect to q. W_{VS} and W_{AV} must be chosen so as to verify simultaneously: $\text{Ker}(W_{\text{VS}}) = \text{Ker}(CLJ)$ and $CLJW^T_{\text{VS}} > 0$ for the first one, $\text{Ker}(W_{\text{AV}}) = \text{Ker}(J_d)$ and $J_d W^T_{\text{AV}} > 0$ for the second one. So, we fix $W_{\text{VS}} = CLJ$ and $W_{\text{AV}} = J_d$. With this property, it can be shown that the task jacobian matrix is positive definite and that the controllers allowing to regulate e_{VS} and e_{AV} exponentially to zero are respectively [1] [7]: $\dot{q}_{\text{VS}} = -\lambda_{\text{VS}} e_{\text{VS}}$ and $\dot{q}_{\text{AV}} = -\lambda_{\text{AV}} e_{\text{AV}}$ with $\lambda_{\text{VS}}, \lambda_{\text{AV}} > 0$. As previously, the global controller is deduced from (9).

Close to the obstacles ($d < d_0$), the robot is driven by $\dot{q}_{\text{AV}}$. The vehicle converges towards ξ_0, realizing perfectly the primary task e_d. It remains to minimize the criterion h_{AV} while respecting the contraint. However, as ϵ is small, the cost minimization does not provide a sufficient linear speed to follow ξ_0. A solution is to define μ to benefit from the visual servoing controller $\dot{q}_{\text{VS}}$ even in the vicinity of the obstacle. Therefore, we define another envelope ξ_- located at a constant distance $d_- < d_0$, such that, between ξ_- and ξ_0, μ varies from 0 to 1, allowing to use a fraction of $\dot{q}_{\text{VS}}$ in the global controller during the avoidance phase. However, the increase of μ limits the importance of $\dot{q}_{\text{VS}}$ in the global control law, and we must choose a large gain λ_{AV} to amplify e_{AV}. Using this control structure, it is hard to prove the stability of the global controller as two different controls act at the same time. Moreover, during the avoidance phase, the visual features evolution is perturbated as the initial vision based task is no more considered as a primary task. Nonetheless, the target will be kept in the line of sight of the camera if the constrained minimization of h_{AV} is sufficient. As the avoidance is a primary objective, non collision is guaranteed. A significant improvement of this method could be to define the linear velocity externally as before. In this way, μ could be defined to insure the mutual exclusion of $\dot{q}_{\text{VS}}$ and $\dot{q}_{\text{AV}}$, guaranteeing the feasability of the task. Another way to prevent the robot from stopping on the security envelope is to keep the vision based task as a primary objective, even during the obstacle avoidance phase. In this way, we benefit from the visual servoing attraction to pass round the obstacle, but the non collision is no more guaranteed (see [4] for more details and simulation results).

6 Simulation results

1- Simulations for the first method: The initial configuration of the robot is defined by $[-15\ 0\ \frac{\pi}{4}]$. The obstacle is a vertical cylinder of radius 1 m centered at the origin $(0, 0)$. The reference distances are $d_+ = 5$ m, $d_0 = 3$ m and $d_- = 2$ m. The maximal velocities are respectively: $v_{\max} = 0.9$ m/s, $\omega_{\max} = 1$ rad/s, and $\dot{q}_{1\max} = 2$ rad/s. The security velocity is $v_{sec} = 0.5$ m/s. Figures 4 and 5 represent respectively the trajectory of the robot and the evolution of the image features. So long as the robot is outside the zone delimited by ξ_0 the visual servoing control steers the robot. The robot centers the visual features in the image and starts converging towards the target. As soon as $d \leq d_+$, v decreases to equal v_{sec} on ξ_-. At that time, as $\mu = 1$, the avoidance starts and the robot follows the envelop. Figures 6, 7 and 8 represent the velocity profiles. The avoidance phase stops when the camera axis becomes tangent to the envelop. Finally, close to the target (when $|e_1| < \epsilon$), we switch to the execution of the full rank task (2) to position the camera perpendicularly to the target.

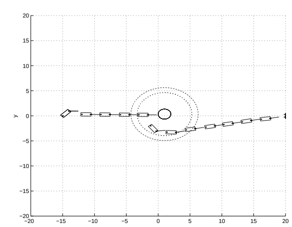

Figure 4: Robot trajectory: method 1

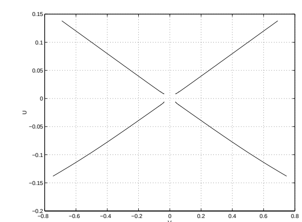

Figure 5: Image features for method 1

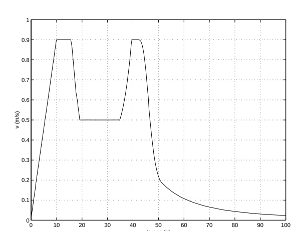

Figure 6: v for method 1

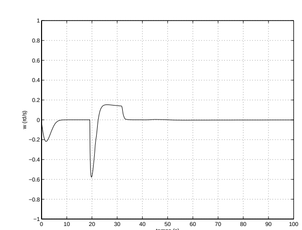

Figure 7: ω for method 1

2- Simulations for the second method: The initial robot configuration is $q^T = [0.7\ 7\ 0\ 90\ 0]$, $d_0 = 0.6$ m, $d_+ = 0.7$ m, and $d_- = 0.5$ m. The maximal bounds on the velocities are: $v < 0.9$ m/s, $\omega < 1$ rad/s, $\dot{q}_1 < 1.4$ rad/s, and $\dot{q}_5 < 2$ rad/s, $\lambda = 0.1$. The robot trajectory

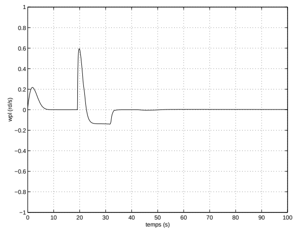

Figure 8: $\dot{q}_1$ for method 1

and the image features are respectively represented on figures 9 and 10. The evolution of μ is given on figure 11. and shows that the avoidance strategy relies on three steps: first of all, the robot is outside the dangerous zone ($d > d_+$), and μ is fixed to 0. In this case, the vehicle executes the vision based task while maintaining q_5 to its nominal value q_5^* and the control variable $\dot{q}_5$ equals 0 as $q_5 = q_5^*$ at the beginning of the task (see figure 16). When the vehicle enters a neighbourhood of the obstacle ($d < d_+$), μ increases and tends to 1 as it approaches ξ_0. During this phase, thanks to the redundancy, the arm compensates the avoidance movement to keep on performing the positioning task perfectly while the robot passes round the obstacle. The evolution of $\det(J_T)$ (figure 12) shows that the visual servoing task and the passing round movement remain compatible during the whole execution of the mission.

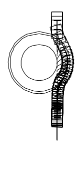

Figure 9: Robot trajectory: method 2

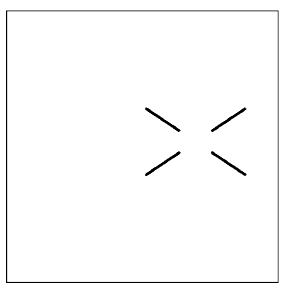

Figure 10: Image features for method 2

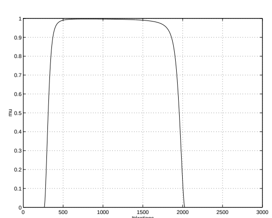

Figure 11: Evolution of μ for method 2

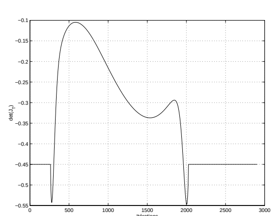

Figure 12: $\det(J_T)$ for method 2

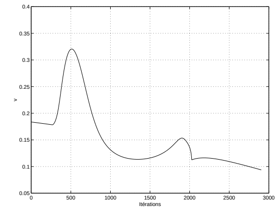

Figure 13: v for method 2

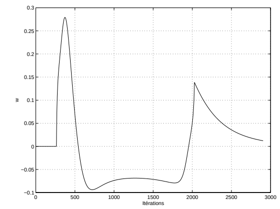

Figure 14: ω for method 2

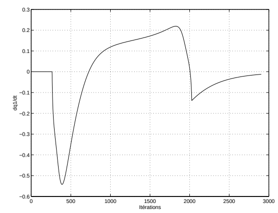

Figure 15: $\dot{q}_1$ for method 2

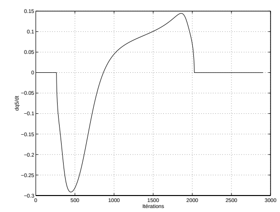

Figure 16: $\dot{q}_5$ for method 2

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