

# USING REDUNDANCY TO AVOID SIMULTANEOUSLY OCCLUSIONS AND COLLISIONS WHILE PERFORMING A VISION-BASED TASK AMIDST OBSTACLES

*D. Folio*<sup>†\*</sup>, *V. Cadenat*<sup>†</sup>

LAAS/CNRS,  
7 Avenue du Colonel Roche,  
31077 Toulouse Cedex 4, France

## ABSTRACT

This article presents a redundancy-based control strategy allowing a mobile robot to avoid simultaneously occlusions and obstacles while performing a vision-based task. The proposed method relies on the continuous switch between two controllers realizing respectively the nominal vision-based task and the occlusion and obstacle avoidance. Simulation results are presented at the end of the paper.

## 1. INTRODUCTION

Visual servoing techniques aim at controlling the robot motion using visual features provided by a camera which can be either directly mounted on the robot or positioned in the environment [1][2]. Different approaches allow to design such control laws. Among them, the task function formalism [3] appears as a very powerful tool for designing sensor-based controllers. Indeed, this formalism can be applied to manipulator arms as well as to mobile robots, provided that, in this last case, the camera is able to move independently from the base [4][5]. However, the visual servoing techniques mentioned above require that the image features remain always in the field of view of the camera, and that they are never occluded during the whole execution of the task. Most of the works which address this kind of problems are dedicated to manipulator arms. The proposed method relies on 3D model-based tracking techniques [6][7] or on 2D algorithms based either on path planning in the image [8] or redundancy schemes [9].

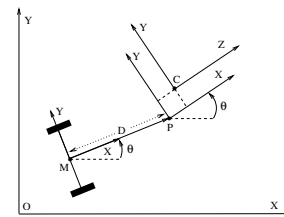
In this paper, we focus on the sensor-based navigation of a nonholonomic mobile robot equipped with an ultrasonic sensor belt and a camera mounted on a pan-platform. Our goal is to perform a nominal vision-based task in a cluttered environment. It is then necessary not only to preserve the image features visibility but also to prevent the mobile base from colliding with the obstacles. The issue is then quite different from the manipulator arms case. Indeed, we consider a robotic system with few available degrees of free-

dom (only three instead of six for example in [9]), different mechanical constraints (nonholonomy), and stronger requirements on robot safety. Previous works [10][11] have focused on a similar navigation problem amidst obstacles. However, as they were a first step towards the realization of complex sensor-based tasks, they were restricted to the case where occlusions could not occur and the encountered obstacles were supposed to be lower than the camera. Therefore, in this article, we aim at extending these methods to avoid occlusions and collisions whenever needed. The developed strategy consists in switching continuously between two controllers depending on the environment to perform either the nominal vision-based task or to benefit from redundancy to avoid simultaneously occlusions and obstacles.

The paper is organized as follows: System modelling and problem statement are given in section 2. The different controllers and the control strategy are presented in section 3. Finally, simulation results are described in section 4.

## 2. MODELLING AND PROBLEM STATEMENT

We consider a cart-like robot with a CCD camera mounted on a pan platform. The kinematics of the system are de-



**Fig. 1.** The mobile robot with pan-platform

duced from the whole hand-eye modelling given in [5].

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \\ \dot{\theta}_{pl} \end{pmatrix} = \begin{pmatrix} \cos \theta & 0 & 0 \\ \sin \theta & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} v \\ \omega \\ \varpi \end{pmatrix} \quad (1)$$

$(x, y)$  are the coordinates of the robot reference point  $M$  with respect to the world frame  $\mathcal{F}_O$ .  $\theta$  and  $\theta_{pl}$  are respec-

\*This work is supported by the European Social Fund.

†emails: dfolio@laas.fr, cadenat@laas.fr

tively the direction of the robot and the direction of the pan-platform with respect to the  $x$ -axis.  $P$  is the pan-platform center of rotation and  $D_x$  the distance between  $M$  and  $P$ . We consider the successive frames:  $\mathcal{F}_M$  ( $M, x_M, y_M, z_M$ ) linked to the robot,  $\mathcal{F}_P$  ( $P, x_P, y_P, z_P$ ) attached to the pan-platform, and  $\mathcal{F}_C$  ( $C, x_C, y_C, z_C$ ) linked to the camera. The transformation between  $\mathcal{F}_P$  and  $\mathcal{F}_C$  is deduced from a hand-eye calibration method. It consists of an horizontal translation of vector  $(a, b, 0)^T$  and a rotation of angle  $\frac{\pi}{2}$  about the  $y_P$ -axis. The control input is defined by the vector  $\dot{q} = (v, \omega, \varpi)^T$ , where  $v$  and  $\omega$  are the linear and the angular velocities of the cart, and  $\varpi$  is the pan-platform angular velocity with respect to  $\mathcal{F}_M$ . Let  $T^c = (V_{\mathcal{F}_C/\mathcal{F}_O}^c, \Omega_{\mathcal{F}_C/\mathcal{F}_O}^c)^T$  be the kinematic screw representing the translational and rotational velocity of  $\mathcal{F}_C$  with respect to  $\mathcal{F}_O$ , expressed in  $\mathcal{F}_C$ . The kinematic screw is related to the joint velocity vector by the robot jacobian  $J$ :  $T^c = J\dot{q}$ . As the camera is constrained to move horizontally, it is sufficient to consider a reduced kinematic screw  $T_{\text{red}}^c$ , and a reduced jacobian matrix<sup>1</sup>  $J_{\text{red}}$  as follows:

$$T_{\text{red}}^c = \begin{pmatrix} -\sin(\theta_{pl} - \theta) & D_x \cos(\theta_{pl} - \theta) + a & a \\ \cos(\theta_{pl} - \theta) & D_x \sin(\theta_{pl} - \theta) - b & -b \\ 0 & -1 & -1 \end{pmatrix} \begin{pmatrix} v \\ \omega \\ \varpi \end{pmatrix} \quad (2)$$

In addition to the CCD camera, the robot is equipped with an ultrasonic (US) sensors belt which provides a set of data characterizing locally the closest obstacle.

**The problem:** We consider the problem of determining a sensor-based closed-loop controller for driving the robot until the camera is positioned in front of a target while avoiding occlusions and obstacles when necessary. For the problem to be well stated, we suppose that no obstacle lies in a close neighborhood of the target.

### 3. CONTROLLER DESIGN

In this section, our goal is to design two controllers allowing to realize respectively the nominal vision-based task and the avoidance of both occlusions and collisions.

#### 3.1. The nominal vision-based task

We first suppose that occlusions do not occur and we address the problem of performing a vision-based navigation task in the free space. We consider the visual servoing technique introduced in [4]. This approach relies on the task function formalism, which consists in expressing the desired task as a task function  $e$  to be regulated to zero [3]. A sufficient condition that guarantees the control problem to be well conditioned is that  $e$  is  $\rho$ -admissible. Indeed, this property ensures the existence of a diffeomorphism between the task space and the state space, so that the ideal

<sup>1</sup>As  $J_{\text{red}}$  is a regular matrix, the camera motion can be proven to be holonomic.

trajectory  $q_r(t)$  corresponding to  $e = 0$  is unique. This condition is fulfilled if  $\frac{\partial e}{\partial q}$  is regular around  $q_r$  [3].

In our application, the target is made of 4 points, defining an 8-dimensional vector of visual signals  $s$  in the camera plane. At each configuration of the robot, the variation of the signals  $\dot{s}$  is related to the kinematic screw  $T_{\text{red}}^c$  by means of the interaction matrix  $L_{\text{red}}$  [4]:

$$\dot{s} = L_{\text{red}} T_{\text{red}}^c \quad (3)$$

For a point  $p$  of coordinates  $(x, y, z)^T$  in  $\mathcal{F}_C$  projected into a point  $P(X, Y)$  in the image plane (see figure 2),  $L_{\text{red}}$  is deduced from the optic flow equations [4] and given by the following matrix  $L_{\text{red}}$  which has a reduced number of columns to be compatible with the dimension of  $T_{\text{red}}^c$ :

$$L_{\text{red}} = \begin{bmatrix} 0 & \frac{X}{z} & XY \\ -\frac{1}{Z} & \frac{Y}{Z} & 1 + Y^2 \end{bmatrix} \quad (4)$$

Following the task function formalism, the task is defined as the regulation of an error function  $e_{\text{vs}}$  to zero (vs stands for “visual servoing”):

$$e_{\text{vs}}(q(t)) = C(s(q(t)) - s^*) \quad (5)$$

where  $s^*$  is the desired value of the visual signal and  $q = [l, \theta, \theta_{pl}]^T$ ,  $l$  representing the curvilinear abscissa of the robot. As the target is fixed,  $s$  depends only on  $q(t)$  and  $s^*$  takes a constant value.  $C$  is a full-rank  $3 \times 8$  combination matrix allowing to take into account more visual features than available degrees of freedom. A simple way to choose  $C$  is to consider the pseudo-inverse of the interaction matrix  $L_{\text{red}}$ , as proposed in [4]. In this way, the task jacobian  $\frac{\partial e_{\text{vs}}}{\partial q} = CL_{\text{red}}J_{\text{red}}$  can be simplified into  $J_{\text{red}}$ , which is always invertible as  $\det(J_{\text{red}}) = D_x \neq 0$ . The  $\rho$ -admissibility property is then insured. The control law design relies on this property. Indeed, classically, a kinematic controller can be determined by imposing an exponential convergence of  $e_{\text{vs}}$  to zero:

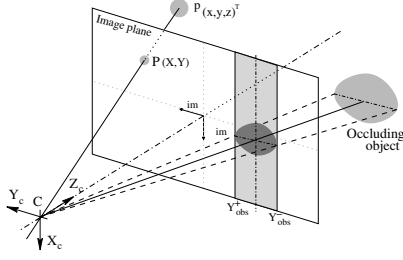
$$\dot{e}_{\text{vs}} = CL_{\text{red}}J_{\text{red}}\dot{q} = J_{\text{red}}\dot{q} = -\lambda_{\text{vs}}e_{\text{vs}} \quad (6)$$

where  $\lambda_{\text{vs}}$  is a positive scalar or a positive definite matrix. From this last relation together with equations (2), (3), (5) and thanks to the  $\rho$ -admissibility property, we can deduce:

$$\dot{q} = \dot{q}_{\text{vs}} = -\lambda_{\text{vs}}J_{\text{red}}^{-1}e_{\text{vs}} \quad (7)$$

#### 3.2. The occlusion avoidance task

Now, we suppose that an occluding object  $\mathcal{O}$  is present in the camera line of sight. Its projection appears in the image plane as shown on figure 2 and we denote by  $Y_{\text{obs}}^+$  and  $Y_{\text{obs}}^-$  the ordinates of its left and right borders.  $X_{\text{im}}$  and  $Y_{\text{im}}$  correspond to the axes of the frame attached to the image plane. The chosen strategy to avoid occlusions only relies on the detection of the two borders of  $\mathcal{O}$ . As the camera is constrained to move in the horizontal plane, there is no loss of generality in stating the reasoning on  $Y_{\text{obs}}^-$  and  $Y_{\text{obs}}^+$ .



**Fig. 2.** Projection of the occluding object in the image plane

Our goal is to define a task function allowing to preserve the visibility of the visual features in the image and to avoid collisions when an obstacle (which can be the occluding object or not<sup>2</sup>) becomes dangerous for the mobile base. To this aim, we have chosen to use the redundant task function formalism [3]. This formalism has been already used for manipulator arms to perform a vision-based task while following a trajectory [4] or avoiding joint limits, singularities [12][13] and even occlusions [9]. It has also been used to avoid obstacles in visually guided navigation tasks for mobile robots [11].

Let  $e_1$  be a redundant task, that is a low-dimensional task which does not constraint all degrees of freedom of the robot. Therefore,  $e_1$  is not  $\rho$ -admissible and an infinity of ideal trajectories  $q_r$  corresponds to the regulation of  $e_1$  to zero. The basic idea of the formalism is to benefit from this redundancy to perform an additional objective. This latter can be modelled as a cost function  $h$  to be minimized under the constraint that  $e_1$  is perfectly performed. In that case, the resolution of this optimization problem leads one to define  $e$  as follows (see [3] for details):

$$e = W^+ e_1 + \beta(I - W^+ W)g$$

where  $W^+ = W^T(WW^T)^{-1}$  is the pseudo-inverse of  $W$ ,  $g = \frac{\partial h}{\partial q}$  and  $\beta$  is a positive scalar, sufficiently small in the sense defined in [3]. Under some assumptions (which are verified if  $W = \frac{\partial e_1}{\partial q}$ ), the task jacobian  $\frac{\partial e}{\partial q}$  is positive-definite around  $q_r$ , insuring that  $e$  is  $\rho$ -admissible [3].

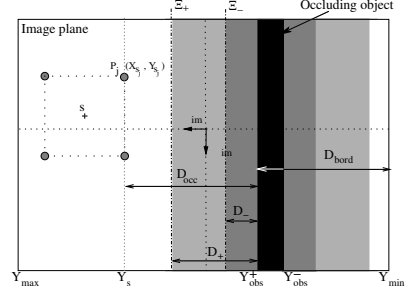
Our objective is to apply these theoretical results to avoid both occlusions and obstacles. We have chosen to define the occlusion avoidance as the redundant task, as it must be executed since the occluding object is detected in the image. The obstacle avoidance will then be modelled as a criterion  $h_{ob}$  to be minimized under the constraint that the redundant task is perfectly performed. In this way, it will be possible to modify the trajectory of the mobile base whenever necessary. Following the redundant task function formalism, we propose the following task function  $e_{o2a}$  ( $o2a$  the acronym of ‘‘occlusion and obstacle avoidance’’):

$$e_{o2a}(q(t)) = W_{occ}^+ e_{occ} + \beta_{o2a}(I - W_{occ}^+ W_{occ})g_{ob} \quad (8)$$

<sup>2</sup>The presence of an occluding object in the image does not necessarily mean that a collision may occur, as an obstacle may be detected by the camera before it becomes dangerous for the mobile base.

where  $e_{occ}$  represents the redundant task function allowing to avoid the occlusions,  $W_{occ} = \frac{\partial e_{occ}}{\partial q}$ ,  $\beta_{o2a}$  is a positive scalar to be fixed and  $g_{ob} = \frac{\partial h_{ob}}{\partial q}$ .

- **Occlusion avoidance:** First, we address the problem of defining a suitable redundant task function  $e_{occ}$  to avoid occlusions. To this aim, let us consider figure 3.



**Fig. 3.** Relevant distances for occlusion avoidance

We denote by  $(X_{s_j}, Y_{s_j})$  the coordinates of each point  $P_j$  of the target in the image frame,  $Y_{min}$  and  $Y_{max}$  representing the ordinates of the two image sides. We introduce the following distances:

-  $D_{occ}$  characterizes the distance before occlusion, that is the shortest distance between the visual features  $s$  and the occluding object  $\mathcal{O}$ . It can be defined as:

$$D_{occ} = \min \left( \min_j |Y_j - Y_{obs}^+|, \min_j |Y_j - Y_{obs}^-| \right) = |Y_s - Y_{occ}|$$

where  $Y_s$  is the ordinate of the closest point  $P_j$  to object  $\mathcal{O}$  and  $Y_{occ}$  the closest border of  $\mathcal{O}$  to the visual features (in the case of figure 3,  $Y_{occ} = Y_{obs}^+$ ).

-  $D_{bord}$  represents the distance separating the occluding object  $\mathcal{O}$  and the opposite image side to the visual features.

$$D_{bord} = \min \left( |Y_{obs}^+ - Y_{max}|, |Y_{obs}^- - Y_{min}| \right) = |Y_{occ} - Y_{bord}|$$

where  $Y_{bord} = Y_{max}$  or  $Y_{min}$  depending on the image border towards which the occluding object must move to leave the image without occluding the target (see figure 3).

-  $D_+$  defines an envelope  $\Xi_+$  delimiting the region inside which the risk of occlusion is detected.

-  $D_-$  defines an envelope  $\Xi_-$  surrounding the critical zone inside which the danger of occlusion is the highest. It will be used in the sequel to determine the global controller.

**Remark 1** Figure 3 represents the case where only one occluding object appears in the image. If several objects are simultaneously detected, we consider the closest one to the target in the image. Now, if at least two of them are detected at the same distance from the visual features, we have to choose one object among the closest ones to preserve the robot from getting stuck in local minimas.

From these definitions, we propose the following redundant task function  $e_{occ}$ :

$$e_{occ} = \left( \frac{1}{D_{occ}} - \frac{1}{D_{max}} \quad D_{bord} \right)^T \quad (9)$$

where  $D_{\max} = \frac{Y_{\max} - Y_{\min}}{2}$  is a constant distance representing the maximal value which can be reached by  $D_{\text{occ}}$ . The first component allows to avoid target occlusions: indeed, it increases when the occluding object is getting closer to the visual features and becomes infinite when  $D_{\text{occ}}$  tends to zero. On the contrary, it decreases when the occluding object is moving far from the visual features and vanishes when  $D_{\text{occ}} = D_{\max}$ . The second component makes the occluding object leave the image, which is realized when  $D_{\text{bord}}$  vanishes. Let us remark that these two tasks must be compatible (that is, they can be realized simultaneously) in order to guarantee the control problem to be well stated. This condition is fulfilled by construction thanks to the choice of  $D_{\text{occ}}$  and  $D_{\text{bord}}$  (see figure 3). Now, let us determine  $W_{\text{occ}} = \frac{\partial e_{\text{occ}}}{\partial q}$ . We get :

$$W_{\text{occ}} = \left( -\frac{1}{D_{\text{occ}}^2} \varepsilon_{\text{occ}} \left( \frac{\partial Y_s}{\partial q} - \frac{\partial Y_{\text{occ}}}{\partial q} \right) \quad \varepsilon_{\text{bord}} \frac{\partial Y_{\text{occ}}}{\partial q} \right)^T$$

where  $\varepsilon_{\text{occ}} = \text{sign}(Y_s - Y_{\text{occ}})$  and  $\varepsilon_{\text{bord}} = \text{sign}(Y_{\text{occ}} - Y_{\text{bord}})$  while  $\frac{\partial Y_s}{\partial q}$  and  $\frac{\partial Y_{\text{occ}}}{\partial q}$  are deduced from the optic flow equations as follows:

$$\begin{cases} \frac{\partial Y_s}{\partial q} &= \begin{pmatrix} -\frac{1}{z_s} & \frac{Y_s}{z_s} & 1 + Y_s^2 \end{pmatrix} J_{\text{red}} \\ \frac{\partial Y_{\text{occ}}}{\partial q} &= \begin{pmatrix} -\frac{1}{z_{\text{occ}}} & \frac{Y_{\text{occ}}}{z_{\text{occ}}} & 1 + Y_{\text{occ}}^2 \end{pmatrix} J_{\text{red}} \end{cases} \quad (10)$$

where  $z_s$  and  $z_{\text{occ}}$  are the depth of the target and of the occluding object.

- **Obstacle avoidance:** Now, we address the problem of finding a criterion  $h_{\text{ob}}$  allowing to avoid the obstacles. The literature provides different approaches to answer this kind of problem. See for example the well-known potential field methods [10][14][15]. In this work, we have chosen to use path following techniques to define  $h_{\text{ob}}$ .

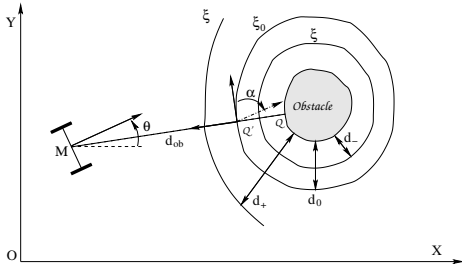


Fig. 4. Obstacle avoidance

Our avoidance strategy is based on the US data from which we compute a couple  $(d_{\text{ob}}, \alpha)$ .  $d_{\text{ob}}$  represents the signed distance between  $M$  and the closest point  $Q$  on the obstacle, while  $\alpha$  is the angle between the tangent to the obstacle at  $Q$  and the robot direction (see figure 4). To build our strategy, we define around each obstacle three envelopes. The first one  $\xi_+$ , located at a distance  $d_+ > 0$ , surrounds the zone inside which the obstacle is detected by the robot. For the

problem to be well stated, the distance between two obstacles is assumed to be greater than  $2d_+$  to prevent the robot from considering several obstacles simultaneously. The second one  $\xi_0$ , located at a lower distance  $d_0 > 0$ , constitutes the virtual path along which the reference point  $M$  will move around the obstacle. The last one  $\xi_-$  defines the region inside which the risk of collision is maximal (this envelope will be used in the sequel to define the global controller). Using the path following formalism introduced in [16], we define a mobile frame on  $\xi_0$  whose origin  $Q'$  is the orthogonal projection of  $M$ . Let  $\delta = d_{\text{ob}} - d_0$  be the signed distance between  $M$  and  $Q'$ . With respect to the moving frame, the dynamics of the error terms  $(\delta, \alpha)$  is described by the following system:

$$\begin{cases} \dot{\delta} = v \sin \alpha \\ \dot{\alpha} = \omega - v \chi \cos \alpha \end{cases} \quad \text{with } \chi = \frac{\frac{\sigma}{R}}{1 + \frac{\sigma}{R} \delta} \quad (11)$$

where  $R$  is the curvature radius of the obstacle,  $\sigma = \{-1, 0, +1\}$  depending on the sense of the robot motion around the obstacle<sup>3</sup>. The path following problem aims at finding a controller  $\omega$  allowing to steer the pair  $(\delta, \alpha)$  to  $(0, 0)$  under the assumption that  $v$  always remains nonzero. Therefore, in our case, we have to find a criterion  $h_{\text{ob}}$  so that its minimization makes  $\delta$  and  $\alpha$  vanish. The path following literature proposes different approaches to fulfill this objective. One of them relies on sliding mode techniques and consists in defining a sliding variable  $z = f(\delta, \alpha)$  so that its regulation to zero induces the one of both  $\delta$  and  $\alpha$ . The choice of  $h_{\text{ob}}$  relies on this idea. We propose the quadratic criterion:

$$h_{\text{ob}} = \frac{1}{2}(\delta + k\alpha)^2 \quad (12)$$

where  $k$  is a positive gain to be fixed<sup>4</sup>. Indeed, the works developed in [17] show that the term  $\delta + k\alpha$  can be seen as a sliding variable and that its regulation to zero makes both  $\delta$  and  $\alpha$  vanish. A complete proof is given in [17]. Therefore, the minimization of  $h_{\text{ob}}$  will allow to avoid the obstacle.

At this step, the task function  $e_{\text{o2a}}$  guaranteeing the occlusion and the obstacle avoidance is completely determined, as  $g_{\text{ob}}$  can be easily deduced from equations (11) and (12). Now, it remains to design a controller allowing to regulate  $e_{\text{o2a}}$  to zero. As  $W_{\text{o2a}}$  and  $\beta_{\text{o2a}}$  are chosen to fulfill the assumptions of the redundant task formalism [3], the task jacobian  $J_{\text{o2a}} = \frac{\partial e_{\text{o2a}}}{\partial q}$  is positive definite around the ideal trajectory and  $e_{\text{o2a}}$  is  $\rho$ -admissible. As well, this result allows to simplify the control synthesis. Indeed, it can be shown that a controller making  $e_{\text{o2a}}$  vanish is given by [4]:

$$\dot{q} = \dot{q}_{\text{o2a}} = -\lambda_{\text{o2a}} e_{\text{o2a}} \quad (13)$$

where  $\lambda_{\text{o2a}}$  is a positive scalar or a positive definite matrix.

<sup>3</sup>The robot motion sense around the obstacle is chosen to keep the target in the camera line of sight.

<sup>4</sup>The value of  $k$  determines the relative convergence velocity of  $\delta$  and  $\alpha$  as the sliding variable converges.

### 3.3. Global control strategy

There exist two approaches for sequencing tasks. In the first one, the switch between two successive tasks is dynamically performed using either the definition of a differential structure on the robot state space [18], or benefiting from the redundant task function formalism to stack elementary tasks and design control laws guaranteeing smooth transitions [19]. The second class of tasks sequencing techniques relies on convex combinations between either the successive task functions or the successive controllers [5][11]. In that case, applications can be more easily carried out, but it is usually harder to guarantee the feasibility of the task. However, this property is often fulfilled thanks to the short duration of the transition. The proposed control relies on the second approach and the global controller is defined by:

$$\dot{q} = (1 - \mu_{O2a})\dot{q}_{vs} + \mu_{O2a}\dot{q}_{O2a} \quad (14)$$

where  $\dot{q}_{vs}$  and  $\dot{q}_{O2a}$  are respectively given by equations (7) and (13).  $\mu_{O2a} \in [0, 1]$  allows to switch continuously from one controller to the other depending on the environment.

$$\mu_{O2a} = (1 - \mu_{occ})\mu_{coll} + \mu_{occ} \quad (15)$$

where  $\mu_{occ}$  and  $\mu_{coll} \in [0, 1]$  characterize respectively the risk of occlusion and of collision. They are given by:

$$\mu_{occ} \begin{cases} 0 & \text{if } D_{occ} > D_+ \\ 1 & \text{if } D_{occ} < D_- \\ \frac{D_+ - D_{occ}}{D_+ - D_-} & \text{otherwise} \end{cases} \quad \mu_{coll} \begin{cases} 0 & \text{if } d_{ob} > d_+ \\ 1 & \text{if } d_{ob} < d_- \\ \frac{d_+ - d_{ob}}{d_+ - d_-} & \text{otherwise} \end{cases}$$

When there is no risk of occlusion nor collision,  $\mu_{occ} = 0$  and  $\mu_{coll} = 0 \Rightarrow \mu_{O2a} = 0$  and the robot is only controlled by  $\dot{q}_{vs}$ . Now, when an occluding object enters the zone delimited by  $\Xi_+$ ,  $\mu_{occ}$  continuously increases. If there is no collision danger,  $\mu_{coll} = 0$  and the value of  $\mu_{O2a}$  is only fixed by  $\mu_{occ}$ . If an obstacle is detected close to the mobile base ( $d_{ob} < d_+$ ),  $\mu_{coll}$  is continuously increased to reach 1 when the collision danger is maximal ( $d_{ob} < d_-$ ). During this phase, the value of  $\mu_{O2a}$  depends both on the risks of occlusion and collision and the robot is controlled by a linear combination of  $\dot{q}_{vs}$  and  $\dot{q}_{O2a}$ . Finally, if the danger of occlusion becomes maximal,  $\mu_{occ} = 1 \Rightarrow \mu_{O2a} = 1$  and only  $\dot{q}_{O2a}$  is applied to the robot.

## 4. SIMULATION RESULTS

We have simulated two missions consisting in positioning the camera in front of a given target. Different initial robot configurations and different target and obstacles locations have been considered to vary the scenarii and demonstrate the interest of our technique. We have also chosen to clutter the environment with obstacles of various shapes. For each test,  $D_-$  and  $D_+$  have been fixed to 30 and 80 pixels, and  $d_+$ ,  $d_0$ ,  $d_-$  to 0.7m, 0.6m, and 0.4m. The sampling period  $T_s$  is the same as on our real robot, that is  $T_s = 150ms$ .

The obtained results are presented on figures 5, 6, 7 and 8. As shown on these figures, all the chosen tasks are perfectly performed: the robot never collides with the obstacles and the image features remain always visible. The variation of parameters  $\mu_{occ}$  and  $\mu_{coll}$  allows to switch smoothly from one controller to the other depending on the environment.

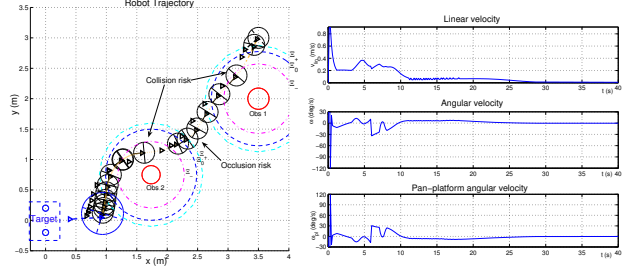


Fig. 5. Robot trajectory and control inputs - Task 1

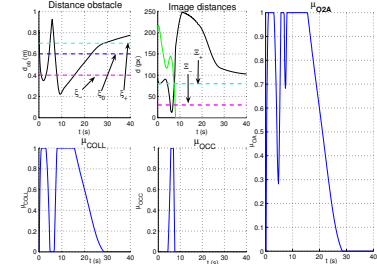


Fig. 6. Evolution of  $D_{occ}$ ,  $d_{ob}$ ,  $\mu_{coll}$ ,  $\mu_{occ}$ , and  $\mu_{O2a}$  - task 1

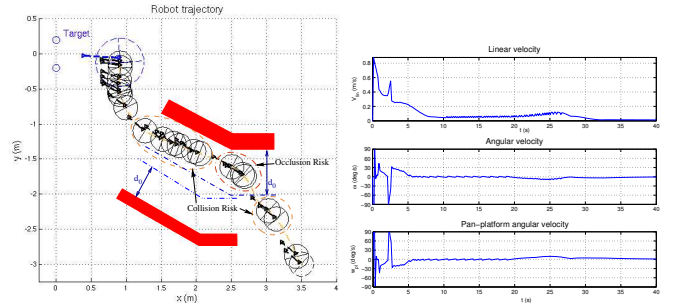


Fig. 7. Robot trajectory and control inputs - Task 2

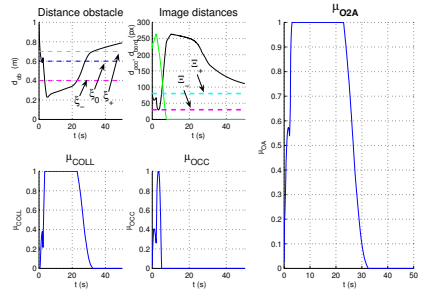


Fig. 8. Evolution of  $D_{occ}$ ,  $d_{ob}$ ,  $\mu_{coll}$ ,  $\mu_{occ}$ , and  $\mu_{O2a}$  - task 2

## 5. CONCLUSION

This article presents a method allowing to avoid simultaneously occlusions and collisions during the execution of a

vision-based task amidst obstacles. The proposed approach shows the interest of defining a redundant task using different sensory data to preserve both target visibility and robot safety. The results are satisfactory and this strategy is currently being experimented on our mobile robots Nomadic SuperScout II. They are equipped with a sixteen ultrasonic sensors belt and with a DFW-VL500 Sony CCD color digital fire wire camera. We are currently improving the image processing to extract not only the visual features but also any other object lying in the camera line of sight. From a more theoretical point of view, some improvements could be done, especially concerning the robot safety. Indeed, our method allows to perform the obstacle avoidance at best under the constraint that the target always remains visible. Therefore, it could be improved by designing a third controller dedicated to the sole obstacle avoidance in addition to the ones previously defined. The redundancy could then be used to perform other objectives such as keeping the target in the camera line of sight while avoiding occlusions.

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