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Avoiding Robot Joint Limits and Kinematic Singularities in Visual Servoing

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Abstract

We propose in this paper solutions to avoid the joint limits and kinematic singularities in visual servoing. We use a control scheme based on the task function approach. It combines the regulation of the selected vision-based task with the minimization of a secondary cost function, which reflects the manipulability of the robot in the vicinity of joint limits and singularities.

1. Introduction

In robotics, and in visual servoing in particular, it is important to avoid the manipulator joint limits and the kinematic singularities. Joint limits are physical limits to the extension of the operational space of the robot, and singularities are peculiar configurations where the manipulator locally looses a degree of freedom. Thus, for such situations, some motions are impossible to be realized Dealing with visual servoing [7][5], which is a closed loop reacting to image data, planning the camera trajectory is not possible. If the control law computes a motion that exceeds a joint limit, or if the robot encounters a kinematic singularity, visual servoing generally fails.

In order to avoid joint limits and singularities, Chang and Dubey [2] have proposed a method based on a weighted least norm solution for a redundant robot. This method does not try to maximize the distance of the joints from their limits but it dampens any motion in their direction. Thus, it avoids unnecessary self-motion and oscillations. An other approach has been proposed by Nelson and Khosla [8]. It consists in minimizing an objective function which realizes a compromise between the visual task (a target tracking) and the avoidance of internal (kinematic singularities) and external (joint limits) singularities. This function is used by exploiting the robot degrees of freedom which are redundant with respect to the visual task. During the execution of the task, the manipulator moves away from its joint limits and singularities. However, such motions can produce important perturbations in the visual servoing since they are generally not compatible with the regulation to zero of the selected image features.

In our case, we have chosen to use a control scheme based on the task function approach [9][5]. It combines the regulation of the vision-based task with the minimization of a cost function. The visual task is considered as a primary and priority task. The cost function is embedded in a secondary task whose only the components which are compatible with the primary task are taken into account (*i.e.*the minimization of the cost function is performed under the constraint that the visual task is realized). As in [8], our approach uses the robot redundancy with respect to the image constraints [9][3], and the cost function to be minimized is based on a measure of the robot manipulability. This measure must be able to compare the different manipulator configurations in order to avoid internal and external singularities. The cost function must reach its maximal value near a singularity and its gradient must be equal to zero when the cost function reaches its minimal value [9].

The next section of this paper recalls the application of the task function approach to visual servoing and the expression of the resulting control law. Section 3 describes the approach proposed to avoid internal and external singularities.

2. Visual Servoing

The *image-based visual servoing* consists in specifying a task as the regulation in the image of a set of visual features[5][7]. Embedding visual servoing in the task function approach [9] allows us to take advantage of general results helpful for the analysis and the synthesis of efficient closed loop control schemes. Control laws in visual servoing are generally expressed in the operational space (*i.e.*, in the camera frame), and then computed in the articular space using the robot inverse Jacobian [6][5][8]. However, in order to combine a visual servoing with the avoidance of either internal and external robot singularities, it is more interesting to directly express the control law in the articular space. Indeed, manipulator joint limits and kinematic singularities are defined in this space. Furthermore, as far as kinematic singularities are concerned, it has the supplementary advantage to be able to perform a visual servoing (or any task) in a kinematic singularity as long as the task is not singular in such configurations. Thus, we first present a modified version of the control law presented in [5] in order to directly control the manipulator in the articular space.

Let us denote $\underline{p}$ the set of selected visual features used in the visual servoing task. To ensure the convergence of $\underline{p}$ to its desired value $\underline{p}_d$, we need to know the interaction matrix $L^T_{\underline{p}}$ defined by the classical equation [5] :

$$\dot{\underline{p}} = L^T_{\underline{p}}(\underline{p}, \underline{P}) T_c \tag{1}$$

where $\dot{\underline{p}}$ is the time variation of $\underline{p}$ due to the camera motion T_c. The parameters $\underline{P}$ involved in $L^T_{\underline{p}}$ represent the depth information between the considered objet and the camera frame. The kinematic screw of the camera is linked to the joint velocity $\dot{\underline{q}}$ of the manipulator by the relation $T_c = J(\underline{q})\dot{\underline{q}}$ where $J(\underline{q})$ is nothing but the robot Jacobian. We simply obtain:

$$\dot{\underline{p}} = H^T_{\underline{p}}(\underline{p}, \underline{P}, \underline{q})\dot{\underline{q}} \quad \text{with} \quad H^T_{\underline{p}}(\underline{p}, \underline{P}, \underline{q}) = L^T_{\underline{p}}(\underline{p}, \underline{P}) J(\underline{q}) \tag{2}$$

The task function $\underline{e}$ to be regulated is thus defined by :

$$\underline{e} = W^+ W \widehat{H}^{T+}_{\underline{p}} (\underline{p} - \underline{p}_d) + (\mathbb{I}_n - W^+ W) g^T_s \tag{3}$$

where

- $\widehat{H}^{T+}_{\underline{p}}$ is the pseudo inverse of a model or an approximation of $\widehat{H}^T_{\underline{p}}$;
- g^T_s is a secondary task, defined as the gradient of a cost function h_s to be minimized ($\underline{g}_s = \frac{\partial h_s}{\partial \underline{q}}$). This task whose aim is here to avoid kinematic singularities and robot joint limits will be described in the next section.
- W is a full rank matrix such that Ker $W =$ Ker $\widehat{H}^T_{\underline{p}}$. W^+W and $\mathbb{I}_n - W^+W$ are two projection operators which guarantee that the camera motion due to the secondary task is compatible with the regulation of $\underline{p}$ to $\underline{p}_d$.

When $\widehat{H}^T_{\underline{p}} = H^T_{\underline{p}}$, the cost function h_s is minimized under the constraint that $\underline{p} = \underline{p}_d$. Indeed, thanks to the choice of matrix W, $\mathbb{I}_n - W^+W$ thus belongs to Ker $H^T_{\underline{p}}$, which means that the realization of the secondary task will have no effect on the vision-based task ($\dot{\underline{p}} = H^T_{\underline{p}}(\mathbb{I}_n - W^+W)\underline{g}^T_s = 0, \forall g^T_s$). On the other hand, if errors are introduced in the model $\widehat{H}^T_{\underline{p}}$ of $H^T_{\underline{p}}$, $\mathbb{I}_n - W^+W$ no more exactly belongs to Ker $H_{\underline{p}}$, which will induce perturbations on the visual task due to the secondary task. Let us finally note that, if the visual task constrains all the n degrees of freedom of the manipulator, we have $W = \mathbb{I}_n$, which leads to $\mathbb{I}_n - W^+W = 0$. It is thus impossible in that case to consider any secondary task.

For making $\underline{e}$ exponentially decreases and then behaves like a first order decoupled system, we get:

$$\dot{\underline{q}}_d = -\lambda \underline{e} - W^+ W \widehat{H}^T_{\underline{p}} \widehat{\frac{\partial \underline{p}}{\partial t}} - (\mathbb{I}_n - W^+ W) \frac{\partial \underline{g}^T_s}{\partial t} \tag{4}$$

where:

- $\dot{\underline{q}}_d$ is the joint velocity given as input to the robot controller;
- λ is the proportional coefficient involved in the exponential convergence of $\underline{e}$;
- $\widehat{\frac{\partial \underline{p}}{\partial t}}$ represents an estimation of a possible autonomous target motion. If the target moves, this estimation has to be introduced in the control law in order to suppress tracking errors. It can be obtained using classical filtering techniques such as Kalman filter [1]. If the scene is static, we can assume that $\frac{\partial \underline{p}}{\partial t} = \widehat{\frac{\partial \underline{p}}{\partial t}} = 0$.

3. Avoiding joint limits and kinematic singularities

As already stated, when the vision-based task does not constrain all the six camera degrees of freedom, a secondary task can be combined with the visual task. Thus we can use the redundant degrees of freedom to perform a singularities (external and internal) avoidance task.

3.1. Joint limits avoidance

The classical approach [9] is to keep the manipulator as far as possible from its joint limits. This means that the manipulator should be located at the middle of each axis extension:

$$h_s = \sum_{i=1}^{n} (q_i - (\frac{q_{i_{min}} + q_{i_{max}}}{2}))^2 \tag{5}$$

where $q_{i_{min}}$ and $q_{i_{max}}$ are the minimum and maximum allowable joint values for the i^{th} joint.

Reaching an optimal position located at the middle of each axis extension is generally not necessary. In fact, the secondary task needs to be used only if one (or several) joint is in the vicinity of a joint limit. We thus define activation thresholds of the secondary task by $\tilde{q}_{i_{min}}$ and $\tilde{q}_{i_{max}}$ such that:

$$\begin{array}{l}\tilde{q}_{i_{min}} = q_{i_{min}} + \rho\,(q_{i_{max}} - q_{i_{min}}) \\ \tilde{q}_{i_{max}} = q_{i_{max}} - \rho\,(q_{i_{max}} - q_{i_{min}})\end{array} \quad (6)$$

where $0 < \rho < 1/2$. The secondary task function is thus given by:

$$h_{s_{joint}} = \frac{\beta}{2}\sum_{i=1}^{n} \frac{s_i^2}{q_{i_{max}} - q_{i_{min}}} \quad (7)$$

$$\text{where} \quad s_i = \begin{cases} q_i - \tilde{q}_{i_{max}} & \text{if } q_i > \tilde{q}_{i_{max}} \\ q_i - \tilde{q}_{i_{min}} & \text{if } q_i < \tilde{q}_{i_{min}} \\ 0 & \text{else} \end{cases} \quad (8)$$

and components of $\underline{g}_s$ and $\frac{\partial \underline{g}_s}{\partial t}$ take the form:

$$g_{s_i} = \begin{cases} \frac{\beta(q_i - \tilde{q}_{i_{max}})}{(q_{i_{max}} - q_{i_{min}})} & \text{if } q_i > \tilde{q}_{i_{max}} \\ \frac{\beta(q_i - \tilde{q}_{i_{min}})}{(q_{i_{max}} - q_{i_{min}})} & \text{if } q_i < \tilde{q}_{i_{min}} \\ 0 & \text{else} \end{cases} \quad , \quad \frac{\partial g_{s_i}}{\partial t} = 0 \quad (9)$$

This cost function to avoid joint limits is similar to the Tsai's manipulability measure used in [8]. It is however more simple since it directly sets the activation thresholds with ρ. Let us finally note that $\underline{g}_s$ and $\frac{\partial \underline{g}_s}{\partial t}$ are continuous, which will ensure a continuous control law.

3.2. Avoiding kinematic singularities

When the robot is in a singular configuration, it looses one or more of its degrees of freedom and it is not possible to inverse its Jacobian (which is no more full rank). Using a control law expressed in the operational space, it is impossible to realize a correct visual servoing if the robot reaches or starts from a singularity. In our case, as explained before, such an avoidance is not necessary if the interaction matrix $H_{\underline{P}}^T$ remains full rank (which is generally the case, even if the robot is in a singular configuration). However, in some cases, and especially if the vision-based task needs a number of degrees of freedom greater than the available one, it is important to be able to avoid the robot kinematic singularities. Like for the problem of joint limits avoidance, it is possible to define a corresponding cost function. When the robot is in a singularity, the determinant of its Jacobian is equal to zero. This well known property allows us to define the cost function $h_{s_{sing}}$ to be minimized as:

$$h_{s_{sing}} = \frac{1}{\det(J(\underline{q}))} \quad (10)$$

In this case, g_{s_i} and $\frac{\partial g_{s_i}}{\partial t}$ are given by:

$$g_{s_i} = -\frac{1}{\det^2(J(\underline{q}))}\frac{\partial \det(J(\underline{q}))}{\partial q_i} \quad , \quad \frac{\partial g_{s_i}}{\partial t} = 0 \quad (11)$$

Since we do not want that $\det(J(\underline{q})) = 0$ (in order to never obtain an infinite value for the cost function and its gradient), we use a saturate determinant such that:

$$\det_{sat}\left(J(\underline{q})\right) = \begin{cases} \det\left(J(\underline{q})\right) & \text{if } \left|\det\left(J(\underline{q})\right)\right| \geq \varepsilon \\ \pm\varepsilon & \text{if } \left|\det\left(J(\underline{q})\right)\right| < \varepsilon \end{cases} \quad (12)$$

3.3. A global task function

The two tasks described above, joint limits and kinematic singularities avoidance, can be easily combined into an unique cost function as:

$$h_s = h_{s_{joint}} + K h_{s_{sing}} \quad (13)$$

where $h_{s_{joint}}$ is the cost function dedicated to joint limits avoidance and $h_{s_{sing}}$ is the cost function dedicated to kinematic singularities avoidance. K is a constant to be tuned which allows to normalize the two tasks and to fix the relative importance of one of the subtask with respect to the other. In [8] the combination of these two tasks is performed by a simple product ($h_s = h_{s_{joint}} h_{s_{sing}}$), thus this relative importance is impossible to determine.

4. Experimental results

The application presented in this paper has been implemented on an experimental testbed composed of a CCD camera mounted on the end effector of a six degrees of freedom cartesian robot.

In a first time, we consider the case of a point. If $\underline{P} = (x, y)$ describes the position of the projection of the center of gravity of an object, the goal is to observe this object at the center of the image: $\underline{P}_d = (0, 0)$. The initial position of the camera, is located in the vicinity of four joint limits (q_1, q_2, q_4 and q_6) and the manipulator is in singularity $q_5 = 90dg$ (see Table 1). If none strategy is used to avoid joint limits, the visual task cannot be achieved (see Figure 1). The error $\underline{p} - \underline{p}_d$ remains equal to (17,7) pixels. However, only two degrees of freedom are necessary to perform the vision-based task, thus four motion components are redundant and

	$q_1(mm)$	$q_2(mm)$	$q_3(mm)$	$q_4(dg)$	$q_5(dg)$	$q_6(dg)$
Joint limit max $q_{i_{max}}$	750	640	500	162	141	90
Joint limit min $q_{i_{min}}$	-740	-750	-496	-171	-5	-90
Initial joint position $q_{i_{init}}$	741	634	170	-145	90	83
Act. Threshold Max	601	501	400	129	126	72
Act. Threshold Min	-591	-611	-396	-138	9	-72
Final position	601	501	171	-121	101	52

Table 1: Positioning with respect to an object: Joint limits and singularity avoidance

can be used to realize the joint limits avoidance. Table 1 presents the obtained results according to the strategy presented in Section 3. The activation thresholds method is efficient from the point of view of the convergence speed, because only four axes are initially involved in the joint limits avoidance (none when the activation limits were reached). We used here an activation threshold equal to 10% of the distance between each axis ($\rho = 0.1$). We can see on Figure 2.c that the robot moves away from its joint limits and reaches the region limited by the activation thresholds (whose corresponding value is ± 0.8 on Figure 2.c). The fact that the robot starts in singularity does not perturb the visual servoing task which is always of full rank 2. Corresponding axis q_5 (see Figure 2.d) moves away from the singularity according to the chosen secondary task. In this experiment we have set $K = 0.0005$ and $\beta = 0.4$.

Results dealing with the tracking of this objects are depicted in Figure 3. The target has unknown translational motions with different amplitudes and directions. To supress tracking errors, we have used a Kalman filter with constant acceleration and colored noise state model (see [1] for details). This task is not achievable if we do not consider a peculiar strategy to avoid joint limits, since the initial robot position is in the vicinity of three joint limits (see Figure 3.c). Once again, the joint limits avoidance is correctly performed and does not perturb the behavior of the target tracking.

5. Conclusion

We have proposed a solution to avoid the joint limits and kinematics singularities in visual servoing. We have chosen to use a control scheme based on the task function approach which combines the regulation of the selected vision-based task with the minimization of a secondary cost function which reflects the manipulability of the robot in the vicinity of internal or external singularities. Finally we can note that, as far as kinematics singularities are concerned, if all the d.o.f of the robot are constrained by the vision-based task, an other approach based on a damped least square method can be used [4]. It will realize, as best as possible, a compromise between the feasibility and the precision of the tasks.

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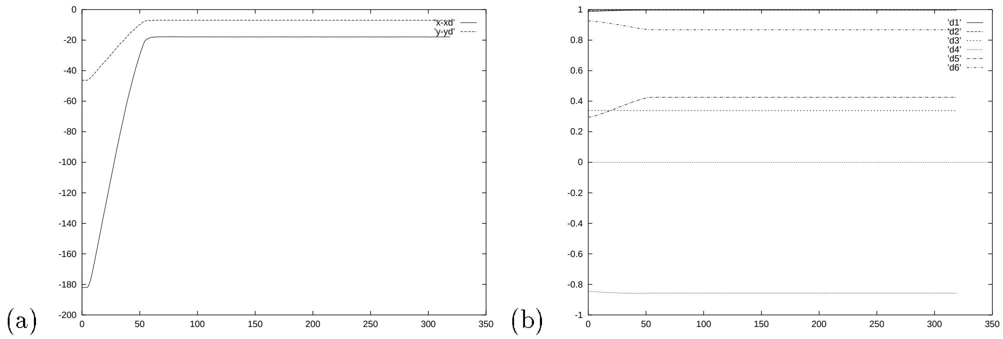

Figure 1: Positioning with respect to an objet without joint limits avoidance : (a) Error $(\underline{p} - \underline{p}_d)$ (in pixels) (b) Distance from the activation thresholds limits $\frac{q_i - q_{i_{end}}}{q_{i_{max}} - q_{i_{end}}}$

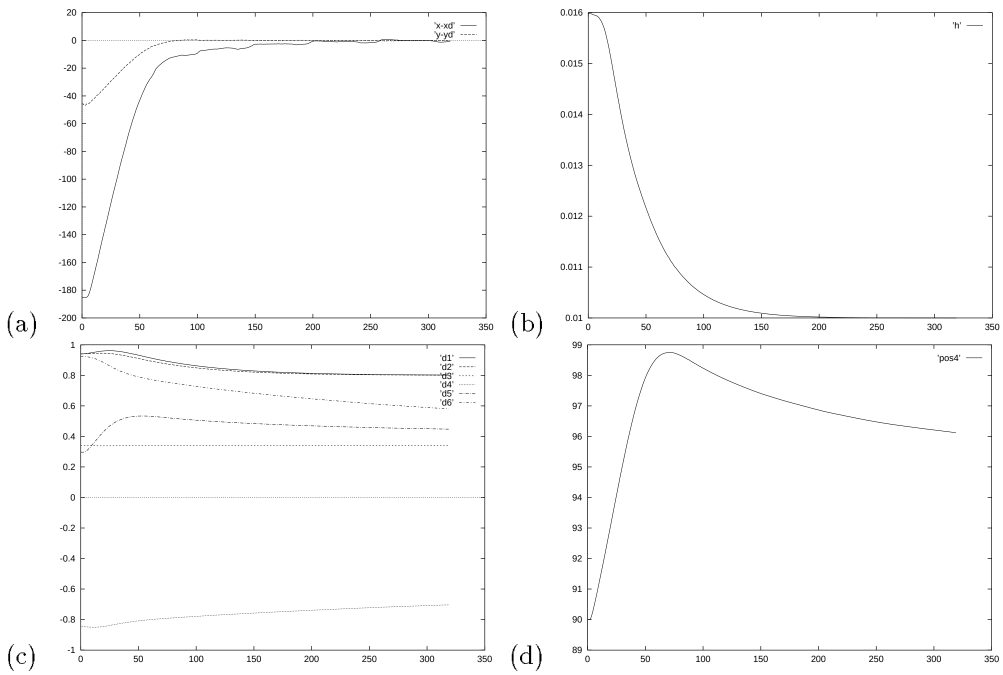

Figure 2: Positioning with respect to an objet with joint limits and singularity avoidance (a) Error $(\underline{P} - \underline{P}_d)$ (in pixels) (b) secondary cost function h_s (c) Distance from the activation thresholds limits $\frac{q_i - q_{i_{end}}}{q_{i_{max}} - q_{i_{end}}}$ (d) position on q_5 (in dg), singularity is for $q_5 = 90^o$

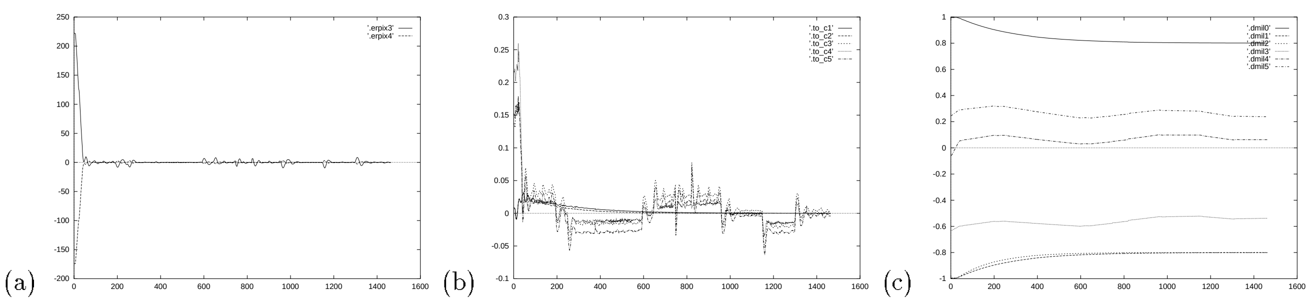

Figure 3: Target tracking and joint limits avoidance (a) error $(\underline{P} - \underline{P}_d)$ (b) joint velocities $\dot{\underline{q}}$ $(m/s$ and $rad/s)$ (c) Distance from the joint limits $\frac{\underline{q} -_{end}}{\underline{q}_{max} - \underline{q}_{end}}$