THE VISIBILITY PROBLEM IN VISUAL SERVOING

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Abstract: This paper deals with the visibility problems occurring during the execution of a visual servoing task. First, a review of the scientific works related with the visibility are recalled and then the solution proposed by the authors is presented and extended to the case of the sudden disappearance of features on the center of the image. Experimental results demonstrate the improvements (stability and continuity) that can be obtained in the performance of the vision-based control task when the weighted features formulation is used.

1 THE VISIBILITY PROBLEM

1.1 Related Work

Traditionally, the visibility problem/constraint has been defined as: *a minimum number of image features must remain in the camera field of view during the control task*. In this section, the different solutions proposed to solve the visibility problem in 2D visual servoing tasks are revised. Many implementations in the literature use the potential fields to keep all feature points inside the viewable portion of the image plane at all times, as the partitioning method (Corke and Hutchinson, 2001) and the path-planning one (Mezouar and Chaumette, 2003).

In Mezouar and Chaummette(Mezouar and Chaumette, 2003), a path planning scheme based on the potential field method is presented. This method allow to introduce constraints in the desired trajectory to be realized. Such constraints are, for instance, to ensure that the object of interest remains in the camera field of view and to avoid the robot joints limits. In counterpart, the analytical forms of the trajectories in the image space are no longer available, and the corresponding camera trajectory deviates from the optimal one when repulsive forces are involved.

In Corke and Hutchinson (Corke and Hutchinson, 2001), a solution to the problem of camera retreat in 2D visual servoing approaches is presented. It is based on decoupling the z-axis translation and rotation from the image Jacobian and then controlling them using simple image features (area, orientation of a image vector). In this paper, the visibility problem is considered as a collision avoidance problem and employed potential field techniques to repel the feature points from the image boundary.

Gans and Hutchinson (Gans and Hutchinson, 2003) have proposed another approach, namely switching between 2D and 3D visual servoing approaches. Thus, whenever the visibility problem of 3D approach is imminent, the control is switched to 2D one. If camera retreat occurs, the control is again switched to 3D approach. In Chesi et al.(Chesi et al., 2002), another switching strategy between several elementary camera movements is proposed.

For a 6 dof visual servoing system, Malis et. al. (Malis and Chaumette, 2002) guarantee that a single feature point remains within the field of view while guaranteeing convergence for a large basin of attraction. Morel et. al.(Morel et al., 1999) extend this idea by decoupling the image-plane motion of a cleverly chosen feature vector a circle containing all the feature points from the rotational motion of the camera; by keeping this conservative feature vector within the image plane, one is guaranteed that all feature points remain within the camera field of view(though self-occlusion avoidance is not guaranteed).

In Zhang and Ostrowski(Zhang and Ostrowski, 2002), optimal control techniques are employed for design of image motion compatible with joint limits and ensuring visibility, the cost function representing a time integral of energy. Similarly, Cowan et al. (Cowan et al., 2002) uses navigation function, representing specially potential field functions with a minimum to be unique by construction.

Another recent solution to this issue is related to the new intrinsic-free visual servoing approach (Malis, 2004). With this approach, it's possible to imple-

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ment a simple focal length control strategy that allows to keep the target in the field of view of the camera during the servoing and recovers at the convergence the focal length value of the reference image without having any previous information about it (Benhimane and Malis, 2003). In Schramm and Morel(F.Schramm and G.Morel, 2004), the approach proposed uses the movement of the camera backwards along its optical axis to keep all points in the camera field of view during the task execution.

1.2 Changes of Visibility in Image Features

Contrary to the scientific works presented before, we proposed the concept of allowing temporary disappearance of image features(only through the image boundary) during the execution of a vision-based control task (Garcia-Aracil and Malis, 2004). In this paper, this concept is extended to the disappearance of features in all the image space.

In (Garcia-Aracil and Malis, 2004), we described the continuity problems of the control law due to the changes of visibility in image features during a visual servoing task and also a solution to this problem when features appear/disappear through the border of the image was proposed. This solution is based on weighting image features depending on the position of them in the image plane Φ_{uv}. The weights are used in order to anticipate in some way the possible discontinuities produced in the control law by the temporary disappearance of image features through the border (Figure 1, features number 1 and 4).

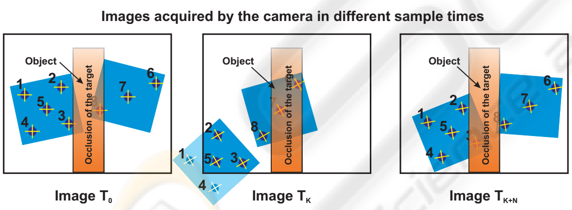


Figure 1: The temporary disappearance concept in vision-based control task.

When the appearance/disappearance of features, it is no produced through the border of the image, for instance, due to a temporary occlusion of the features (Figure 1, features number 3, 6, 7 and 8). The solution proposed in (Garcia-Aracil and Malis, 2004) must be adapted to assure the continuity of the control law. We propose to use two new weights functions to take into account this situation: one of them for the disappearance of features near the center of the image Φ_o^i (Figure 2, green zone) and the other one for the appearance of features near the center of the image Φ_a^i (Perez et al., 2005).

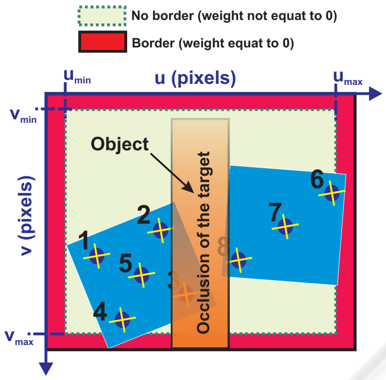


Figure 2: The temporary disappearance concept in vision-based control task.

The global weight function Φ^i which includes the three possible situations commented before is defined as the product of the three weight functions (Φ_{uv}^i, Φ_a^i y Φ_o^i):

$$\Phi^i = \Phi_{uv}^i \cdot \Phi_a^i \cdot \Phi_o^i \quad \text{where} \quad \Phi^i \in [0,1] \tag{1}$$

2 THE SUDDEN DISAPPEARANCE OF FEATURES ON THE CENTER OF THE IMAGE

In this case, the weight Φ_o^i takes into account this situation and after a certain number of steps, this weight reaches its minimum value 0. During the steps needed to reach its minimum, the coordinates of image features must have a value near their last value. The authors think that we have only two possibilities: the first one is to suppose that the coordinates of the image features change slowly and they have their last value during the needed steps so that the weight Φ_o^i reachs its minimum value;the second one is using a prediction filter to predict the next values of the image features during the needed steps so that the weight Φ_o^i reachs its minimum value. After a huge number of simulations, we realize that a prediction filter option is better than considering the last value of image feature.

We have tested the following prediction filters:

Linear Interpolation

The simplest analyzed filter is the Linear Interpolation. This one is base on prediction calculus of the next position aligned with two immediately previous positions.

The Kalman filter

This filter is recommended for systems affected by noise disturbance that cannot be modeled. It makes a *Bayesian* prediction of the state where the system model includes two random variables (*Gaussian* variables) with null average and a well-known covariance (white noise), these variables corresponds to: the system error *v(k)* and the measure error *w(k)*. The *Kalman* filter is based on a recursive expression of prediction and correction: it considers the current state from the prediction and adds a term of proportional correction to the prediction error, so this prediction error is minimized (optimal estimation).

Alphabeta filter

The alpha-beta filter is a particular case of the *Kalman* filter for a constant velocity system model. In this case, the filter gain is considered constant, so it is not calculated for each iteration. Also, it is not necessary the calculus of covariance of estimation and prediction of innovation simplifying the algorithm and decreasing the calculus time.

Alphabetagamma filter

The alpha-beta-gamma ($\alpha\beta\gamma$) filter is again a particular case of the *Kalman* filter, but in this case, it is a filter based on a constant acceleration model system.

***OLOF* filter**

The OLOF filter is a new filter designed at Miguel Hernandez University and the authors think that the use of this filter is recommended if the behavior of the object is unknown a priori and probably the object would have speed, acceleration and jerk changes.

The OLOF filter is a "mix" of some other filters (*LI*, $\alpha\beta$, $\alpha\beta\gamma$, *Kv* (v=cte), *Kv* (a=cte)and *Kv* (j=cte)). Starting with the same weights for each filter, a modification of *Rosenbrock* optimization algorithm was used to adjust these parameters to the optimum values (Gill et al., 1981)(Rosenbrock, 1960)(Conn et al., 1998). After different simulations we have obtained the optimal values.

3 EXPERIMENTAL RESULTS

Experimental results has been obtained using a 6 axis industrial manipulator (Fanuc LR Mate 200iB). The experimental setup used in this work also include one camera (Ueye Industrial camera from IDS) rigidly mounted at the robot end-effector and some surgical objects.

3.1 Control Law

Suppose that n matched points are available in the current image and in the reference features stored. Everyone of these points(current and reference) will have a weight Φ^i which can be computed as it's shown in the previous sections. With them and their weights, a task function can be built:

$$\mathbf{e} = \mathbf{CW}\,(\mathbf{s} - \mathbf{s}^*) \qquad (2)$$

where $\mathbf{W}$ is a $(2n \times 2n)$ diagonal matrix where its elements are the weights Φ^i of the current features.

The derivate of the task function will be:

$$\dot{\mathbf{e}} = \mathbf{CW}\,\dot{\mathbf{s}} + (\mathbf{C}\dot{\mathbf{W}} + \dot{\mathbf{C}}\mathbf{W})(\mathbf{s} - \mathbf{s}^*) \qquad (3)$$

Plugging the equation ($\dot{\mathbf{s}} = \mathbf{L}\,\mathbf{v}$) in (3) we obtain:

$$\dot{\mathbf{e}} = \mathbf{CW}\,\mathbf{Lv} + (\mathbf{C}\dot{\mathbf{W}} + \dot{\mathbf{C}}\mathbf{W})(\mathbf{s} - \mathbf{s}^*) \qquad (4)$$

A simple control law can be obtained by imposing the exponential convergence of the task function to zero ($\dot{\mathbf{e}} = -\lambda\mathbf{e}$), where λ is a positive scalar factor which tunes the speed of convergence:

$$\begin{aligned}\mathbf{v} &= -\lambda\,(\mathbf{CWL})^{-1}\mathbf{e} - (\mathbf{CWL})^{-1}\,(\mathbf{C}\dot{\mathbf{W}} + \\ &+ \dot{\mathbf{C}}\mathbf{W})\,(\mathbf{s} - \mathbf{s}^*) \end{aligned} \qquad (5)$$

if $\mathbf{C}$ is setting to $(\mathbf{W}^*\mathbf{L}^*)^+$,then $(\mathbf{CWL}) > 0$ and the task function converge to zero and, in the absence of local minima and singularities, so does the error $\mathbf{s}-\mathbf{s}^*$. In this case, $\mathbf{C}$ is constant and therefore $\dot{\mathbf{C}} = 0$. Finally substituting $\mathbf{C}$ by $(\mathbf{W}^*\mathbf{L}^*)^+$ in equation (5), we obtain the expression of the camera velocity that is sent to the robot controller:

$$\mathbf{v} = -(\mathbf{W}^*\mathbf{L}^*)^+\,(\lambda\,\mathbf{W} + \dot{\mathbf{W}})\,(\mathbf{s} - \mathbf{s}^*) \qquad (6)$$

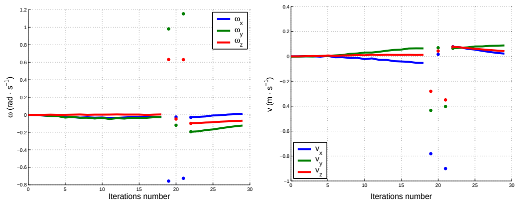
3.2 Results

We compare the weighted and un-weighted 2D visual servoing approaches. In this experiment, the interaction matrix is assumed constant and determined during off-line step using the desired value of the visual features and an approximation of the points depth at the reference camera pose. The goal of the control is to keep the robot in the reference position using the 2D visual servoing approach.

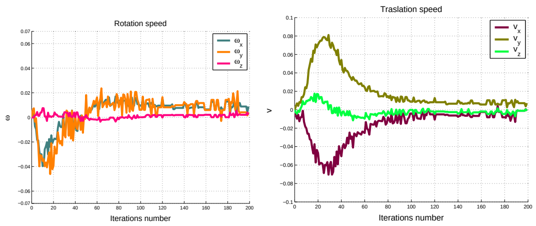
Using the 2D visual servoing approach, the system becomes unstable due to the lost of a feature during the control task(Figure 3(a)3(b)). When the 2D visual servoing approach with weighted features is used, the system is stable although one or more features leave the image plane or something occlude one or more features(Figure 3(c)3(d)).

4 CONCLUSION

In this paper, the visibility problems in visual servoing are presented and a review of the different scientific works which treat this problem are recalled. After that, our solution to this problem is presented and extended to the case of the sudden disappearance of



(a) Rotational velocity (b) Translational velocity



(c) Rotational velocity (Weighted features) (d) Translational velocity (Weighted features)

Figure 3: Experimental results: 2D visual servoing approach.

features on the center of the image. To assure the continuity of the control law in this case, a prediction filter developed by us is used to estimate the coordinates of the occluded image features. With the experimental results, it has been shown that the 2D visual servoing with weighted features is continuous and locally stable in a neighborhood of the equilibrium point.

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