Visual servoing with Respect to a target Sphere Using a Camera/Laser-Stripe sensor

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Abstract—The work presented in this paper fits into the robotics and computer vision generic terms. The problem we seek to resolve is the robotics task accomplishment by using visual information provided by a particular sensor, mounted on a robot end effector. This sensor is constituted by a laser stripe rigidly fixed to a camera, projecting a light plane on the scene.

First of all, we explain approaches employed in robot control from information provided by a vision sensor, and especially the *visual servoing* approach which corresponds to the one we develop. In this case, concerning the passive vision sensor, different works are expressed [7]. Then, after a brief presentation of the advantages of a camera and laser stripe coupling, we develop the modelling of the visual information from a scene constituted of spherical objects. This modelling permits us to establish a relation between the variations of visual information and camera velocities.

Next, this modelling is integrated into the vision based control field [14]. Finally, in our experimental cell, and concerning the positioning task with respect to a sphere, results are presented which prove the robustness and the stability of the control scheme.

I. Introduction

Nowadays, the vision sensor (camera) is more and more essential in order to resolve complex problems of the environment perception. Its miniaturization and recents image processing developments have allowed, firstly, the mounting of the visual sensor on the end effector of a robot, and secondly, the integration of visual information in a robot control loop.

Then, these developments have permitted the conception of many more robotics tasks such as tracking objects and obstacle avoidance. The first works concerning the use of visual information in robot control are due to Sanderson and Weiss [15], [19]. They present two separate approaches. The first approach, commonly called "*Look and Move*", is synthetized in terms of regulation of the end effector situation [2], [3], [18].

So, in this approach, an interpretation step of the end effector situation is necessary. This step is usually obtained with some inaccuracies depending on the visual sensor geometry, environment and robot models. Moreover, the search for the end effector situation is time consuming and may affect the system's overall behaviour.

A second approach, which removes the drawbacks of the previous approach controls the end effector of a robot from visual information. This control scheme which corresponds to the one we develop is called *"visual servoing"*.

A. The visual servoing approach

In this approach, the control is directly specified in terms of regulation in the image. One can notice that this approach has the advantage of avoiding the intermediary step of 3D estimation of the workpiece with regard to the end effector (see Figure 1).

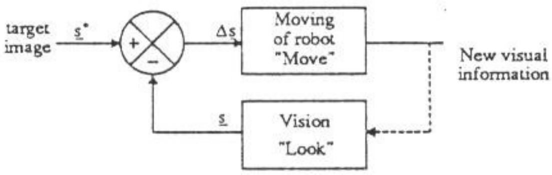

Figure 1: Visual servoing

For a given robotics task, a *target image* is built, corresponding to the desired position of the end effector with regard to the workpiece. Then, a robotics control scheme is developed directly based on image errors between the current image and the target one [5], [7].

It may be shown, that all servoing types, may in general be expressed as the regulation to zero of a function $\underline{e}(\underline{r}, t)$ called *task function* [14]. So, the use of a vision sensor allows us to build up such a task function used in a visual servoing. It is expressed by [14]:

$$\underline{e}(\underline{r}, t) = C[\underline{s}(\underline{r}, t) - \underline{s}^*] \quad (1)$$

where

- $\underline{s}^*$ is considered as a reference target image to be reached in the image frame.
- $\underline{s}(\underline{r}, t)$ is the value of visual information currently observed by the camera. These informations depend on the situation between the end effector of the robot and the scene (noted $\underline{r}$).
- C is a constant matrix, which allows, with goods stability and robustness conditions, to take into account

more visual information than the number of degrees of freedom of the robot.

For a given task, the problem consists, first of all, in choosing relevant visual information to achieve the task, and then in constructing the constant matrix C. This matrix C requires to establish an interaction matrix. The C choice will be discussed afterwards in Section III.

B. The interaction matrix

We formalize the problem in terms of *sensor-based-control* [6] applied to visual servoing. The visual information, provided by the wrist-mounted sensory apparatus, is modelled as a set of *elementary signals* $\underline{s}$ associated to the 2D geometric primitives in the image corresponding to the projection of the 3D primitives in the scene. The interaction between the sensor and the scene is described by a *coupling matrix* $L_{\underline{s}}^T$ which links the behaviour of the signal to the sensor and/or object motion:

$$\dot{\underline{s}} = L_{\underline{s}}^T \cdot \xi \tag{2}$$

where

- $\dot{\underline{s}}$ is the time variation of $\underline{s}$.
- ξ is the object velocity with respect to the sensor (with $\xi = (\underline{T}, \underline{\Omega}) = (T_x, T_y, T_z, \Omega_x, \Omega_y, \Omega_z)^T$).
- $L_{\underline{s}}^T$ is an *interaction matrix* linking the variations of visual information and camera velocities. It perfectly expresses the interaction between the robot and its environment.

The first works concerning the modelling of visual information were developed by Feddema [8], [9]; they concern the modelling of points for a control of four degrees of freedom of a robot (three translations and one rotation).

Next, Espiau et al. modelled a set of low level geometrical primitives such as points, lines, circles and spheres in the case of passive vision [5], [7]. Our work consists in the modelling of visual information by using a sensor called "*active*" in the sense that it is constituted by a camera and laser stripe coupling.

C. Coupling a camera and laser stripe

The use of a laser stripe allows us to suppress illumination problems. Indeed, in a mobile environment, different motions may generate the loss of information in the image frame, and therefore image processing is necessary after each moving. A laser stripe removes this drawback because only the information given by the laser stripe projection onto the scene is detected by the visual sensor.

Laser stripes in robotics have been widely used in real-time tracking of moving objects [17], in many applications allowing the recognition and interpretation of a workpiece surface [1], and also in assembly tasks [4], [10]. In our application, we use two laser stripes rigidly attached to the camera. Each one projects a light plane onto the scene, but we do not search for the three dimensional information. We mainly use visual information provided by the laser stripe projection onto the scene.

Moreover, the visual information is very straightforward and depends on the object geometry. The features are limited to points of discontinuity or lines in a polyhedral scene case. Therefore, image processing is significantly reduced, hence a saving of time which furthers the dynamic of the system.

The only constraint imposed by the laser stripe is to know exactly the position of each laser plane with respect to the camera frame. Knowing various laser plane parameters and also the geometry of the scene objects, we may model visual information from the image. After some modelling works, we may build a control scheme allowing to accomplish a visual servoing.

In the past, interaction matrices were constructed with a camera laser coupling in a polyhedral scene case. In that case, visual information consists of points of discontinuity or lines [11], [12], [16]. In this paper, we present the modelling of visual information in the spherical scene case .

II. Modelling of visual information

In order to model visual information from a spherical scene, it is necessary to select features which will be used in the control scheme. Then, we have to compute the related interaction matrix (see Figure 2).

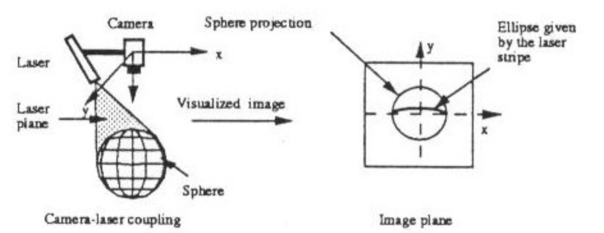

Figure 2: Camera-laser coupling with a sphere

The sphere is represented by its centre $\underline{m}_0 = (x_0 \; y_0 \; z_0)^T$ and its radius r, i.e:

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 - r^2 = 0 \tag{3}$$

The laser rigidly attached to the camera is characterized by a plane equation:

$$ax + by + cz + d = 0 \tag{4}$$

Considering a pinhole camera with unit focal length, a point $\underline{x}(x, y, z)^T$ in 3D space projects into $\underline{X} = (X \; Y \; 1)^T$ on the image frame with:

$$\underline{X} = \frac{1}{z}\underline{x} \tag{5}$$

By using (5) into (4) and (3), we may express the ellipsis equation from the projection in the image of the intersection between the sphere and the laser plane. Obviously, the camera only detects the portion of the ellipsis corresponding to the sphere top side. The equation of this ellipsis is given by [5]:

$$E_1(\underline{X}, \underline{A}) = X^2 + A_1 Y^2 + 2A_2 XY + 2A_3 X + 2A_4 Y + A_5 = 0 \tag{6}$$

$$\text{with} \begin{cases} \underline{X} &= (X, Y) \\ \underline{A} &= (A_1, \ldots, A_5) \end{cases}$$

where

$$\left\{\begin{array}{lcl} A_1 & = & [b^2(z_0^2+y_0^2+x_0^2-r^2)+2bdy_0+d^2]/A_0 \\ A_2 & = & [ab(z_0^2+y_0^2+x_0^2-r^2)+ady_0+bdx_0]/A_0 \\ A_3 & = & [ac(z_0^2+y_0^2+x_0^2-r^2)+adz_0+cdx_0]/A_0 \\ A_4 & = & [bc(z_0^2+y_0^2+x_0^2-r^2)+bdz_0+cdy_0]/A_0 \\ A_5 & = & [c^2(z_0^2+y_0^2+x_0^2-r^2)+2cdz_0+d^2]/A_0 \end{array}\right. \quad (7)$$

and $A_0 = a^2(z_0^2+y_0^2+x_0^2-r^2)+2adx_0+d^2 \neq 0$

In order to establish, the interaction matrix of these parameters, we compute the time variation of $\underline{A}$. We immediately obtain:

$$\dot{\underline{A}} = \sum_{i=1}^{8} \frac{\partial \underline{A}}{\partial \alpha_i}\dot{\alpha}_i \text{ with } \alpha_i = (a,b,c,d,x_0,y_0,z_0,r) \quad (8)$$

In these conditions $\dot{a} = \dot{b} = \dot{c} = \dot{d} = \dot{r} = 0$ because the laser plane is rigidly attached to the camera and the sphere keeps its shape. Moreover $\dot{\underline{m}}_0 = \underline{T} + \underline{\Omega} \wedge \underline{m}_0$ which allows us to compute [11] the interaction matrix $L^T_{\underline{A}}$ related to $\underline{A}$.

All the same, this parametrization confronts us with a problem concerning the parameter extraction $\underline{A}$ at a time of real experimentations. That is why, knowing the ellipsis equation, we may compute other interaction matrices by using other representations in the image. A first method uses the inertia momentums of the ellipsis, a second one searches for points of discontinuity from the intersection of the ellipsis given by the sphere and the ellipsis given by the intersection of the laser stripe and the sphere. In this paper, we only present the case of points of discontinuity.

In order to elaborate the interaction matrix of the point of discontinuity primitive, it is necessary to determine the expression of 2 ellipsis:

- the ellipsis given by the projection into the image of the intersection between the sphere and the laser plane (eq. 6) ;
- the ellipsis given by the sphere projection onto the image.

This second ellipsis (a circle if the sphere is centred in the image) may be represented in a similar way to the first one:

$$E_2(\underline{X},\underline{B}) = X^2 + B_1Y^2 + 2B_2XY + 2B_3X + 2B_4Y + B_5 = 0 \quad (9)$$

$$\text{with} \left\{\begin{array}{lcl} \underline{X} & = & (X,Y) \\ \underline{B} & = & (B_1,\ldots,B_5) \end{array}\right.$$

where

$$\left\{\begin{array}{lcl} B_1 & = & [r^2-x_0^2-z_0^2]/B_0 \\ B_2 & = & [x_0y_0]/B_0 \\ B_3 & = & [x_0z_0]/B_0 \\ B_4 & = & [y_0z_0]/B_0 \\ B_5 & = & [r^2-x_0^2-y_0^2]/B_0 \end{array}\right. \quad (10)$$

and $B_0 = r^2 - y_0^2 - z_0^2$

Knowing these 2 ellipsis expression, we may find the points of discontinuity $\underline{X}_e = (X_e, Y_e)$ which correspond to their intersections. Theoretically, and as a result of the configuration of the camera-laser coupling, there are 2 solutions. Then we may determine the interaction matrix related to each point of discontinuity. We compute the time variation of the expression $E_1(\underline{X},\underline{A})$ and $E_2(\underline{X},\underline{B})$, thus:

$$\dot{E}_1 = \frac{\partial E_1}{\partial \underline{X}_e}\dot{\underline{X}}_e + \frac{\partial E_1}{\partial \underline{A}}\dot{\underline{A}} = 0 \quad (11)$$

$$\dot{E}_2 = \frac{\partial E_2}{\partial \underline{X}_e}\dot{\underline{X}}_e + \frac{\partial E_2}{\partial \underline{B}}\dot{\underline{B}} = 0 \quad (12)$$

The resolution of this linear system with respect to the unknown $\dot{X}_e$, $\dot{Y}_e$ gives the interaction matrix $L^T_{\underline{X}_e}$ of the point of discontinuity, knowing:

- the expressions A_i given by (7), $\dot{A}_i$ given by (8), B_i given by (10) and $\dot{B}_i$ obtained in a similar manner to the interaction matrix of the parameters A_i. These expressions depend on 3D scene parameters and the sphere velocity $(\underline{T},\underline{\Omega})$ with respect to the sensor.
- the coordinates X_e, Y_e of the point of discontinuity extracted after each image acquisition.

After some simplifications [11], the interaction matrix may be expressed by:

$$\dot{\underline{X}}_e = \begin{pmatrix} \dot{X}_e \\ \dot{Y}_e \end{pmatrix} = L^T_{\underline{X}_e} \cdot \xi \quad (13)$$

- **Remarks**: Another method which allows the determination of this interaction matrix mainly uses the cone properties given by the sphere [11].

III. The vision based control

A. Redundancy tasks

We know each robotics task may be conveyed as the regulation to zero, of a function $\underline{e}_1(\underline{r},t)$ which depends on the manipulator robot position and on an object moving. Its motion is then parametrizable by the time variable t. In the vision based task, we have [14]:

$$\underline{e}_1(\underline{r},t) = C[\underline{s}(\underline{r},t) - \underline{s}^\star] \quad (14)$$

where $\underline{s}^\star$ corresponds to the reference target image.

Now, we define the construction of the global task function $\underline{e}(\underline{r},t)$ knowing $\underline{e}_1(\underline{r},t)$. Indeed, when only some axes are used in a robotics task, it may be interesting to use axes, which have no constraint in this first task, in a secondary task. Generally, the realization of a secondary goal is expressed as a minimization of a cost function $h_s(\underline{r},t)$ under the constraint that the main task is achieved, i.e $\underline{e}_1(\underline{r},t) = 0$.

If we consider a main task $J_1 = \frac{\partial \underline{e}_1}{\partial \underline{r}}$ of dimension m and a secondary task $g_s = \frac{\partial h_s}{\partial \underline{r}}$, the determination of axes which are left free by the main task requires to compute the kernel of the matrix J_1 along the ideal trajectory of the robot. In practice, this knowledge is equivalent to the knowledge of a $m \times n$ matrix value function W such that (where the number n is the degrees of freedom of the robot):

$$Ker(W) = Ker(J_1) \quad (15)$$

Once such a matrix is known, a possible global task function may be found [13], [14]:

$$\underline{e} = W^+ \underline{e}_1 + \alpha(\mathbf{I}_n - W^+ W) g_s^T \quad (16)$$

where α is a positive scalar, W^+ the pseudo-inverse of W and $(\mathbf{I}_n - W^+ W)$ an orthogonal projection operator which projects the kernel of J_1.

In the visual signal case, and by using (14), the global task function may be expressed by:

$$\underline{e} = W^+ C[\underline{s}(\underline{r}, t) - \underline{s}^*] + \alpha(\mathbf{I}_n - W^+ W) g_s^T \quad (17)$$

Then, by analogy with (16), and knowing that the interaction matrix $L_{\underline{s}}^T = \frac{\partial \underline{s}}{\partial \underline{r}}$, we may write:

$$J_1 = \frac{\partial \underline{e}_1}{\partial \underline{r}} = C L_{\underline{s}}^T \quad (18)$$

The matrix C have to choose such as the product CL^T is of full rank. Therefore, according to (15), the matrix W may be expressed:

$$Ker(W) = Ker(L_{\underline{s}}^T) \quad (19)$$

B. Stability criteria

A basic control consists in trying to obtain that the task error $\underline{e}(\underline{r}, t)$ approximately behaves like a first-order decoupled system [7]:

$$\dot{\underline{e}} = -\lambda \underline{e} \quad (20)$$

with $\lambda > 0$.

Then, knowing that $\underline{e}(\underline{r}, t)$ depends on the manipulator robot position and on an object moving, we may write:

$$\dot{\underline{e}} = \frac{\partial \underline{e}}{\partial \underline{r}} \xi_c + \frac{\partial \underline{e}}{\partial t} \quad (21)$$

Ideally, ξ_c should be of the form:

$$\xi_c = -\left(\frac{\partial \underline{e}}{\partial \underline{r}}\right)^{-1} (\lambda \underline{e} + \frac{\partial \underline{e}}{\partial t}) \quad (22)$$

Since W and C are constant, and by using the visual task function (16), we have:

$$\frac{\partial \underline{e}}{\partial t} = W^+ \frac{\partial \underline{e}_1}{\partial t} + \alpha(\mathbf{I}_6 - W^+ W) \frac{\partial \underline{g}_s^T}{\partial t} \quad (23)$$

Vector $\frac{\partial \underline{e}_1}{\partial t}$ represents the contribution of a possible autonomous target motion and is in general unknown. It may be shown that an exponential convergence will be ensured under the sufficient condition:

$$C L_{\underline{s}}^T W^T > 0 \quad (24)$$

in the sense that a $n \times n$ matrix A is positive if $x^T A x > 0$ for any nonzero $x \in \mathbf{R}^n$.

This relation allows us to choose the control matrix C from W and $L_{\underline{s}}^T$. for that, we use the pseudo inverse of the interaction matrix related to $\underline{s}^*$. The ideal choice corresponds to:

$$C = W L^{T+}_{|\underline{s}=\underline{s}^*} \quad (25)$$

because the product WW^T is positive.

Moreover, it may be shown that if we consider $\left(\frac{\partial \underline{e}}{\partial \underline{r}}\right)^{-1} = \mathbf{I}_6$ the condition (24) is always ensured. Consequently, if the object is motionless ($\frac{\partial \underline{e}_1}{\partial t} = 0$), the control law may finally be written:

$$\begin{cases} \xi_c = -\lambda \underline{e} - \alpha(\mathbf{I}_6 - W^+ W) \frac{\partial \underline{g}_s^T}{\partial t} \\ \text{with } \underline{e} = W^+ C[\underline{s}(\underline{r}, t) - \underline{s}^*] + \alpha(\mathbf{I}_n - W^+ W) g_s^T \end{cases} \quad (26)$$

This simple control law only requires the regulation of 2 gains. The first one λ depends on the application and the robot dynamic (in our case $\lambda = 0.1$). The second one α gives the preponderance of the secondary task with regard to the main task (with $\alpha < 1$ the main task have the priority).

IV. Results

The task is to position the camera with respect to a sphere in such way that the projection in the image gives a centred circle ($x_0 = y_0 = 0, z_0 = z^*$).

Using still 2 laser stripes to perform this task, we have $\underline{s} = (X_1, Y_1, \ldots, X_4, Y_4)$, where the two first points belong to the laser plane 1 ($a_{l1} = 0$) and the two last one to the laser plane 2 ($b_{l2} = 0$). At the equilibrium position, the sphere is still centred in the image, thus $\underline{s}^* = (X^*, 0, -X^*, 0, 0, Y^*, 0, -Y^*)$ with $X^* = Y^* = r/\sqrt{z^2 - r^2}$.

The interaction matrix $L^T_{|\underline{s}=\underline{s}^*}$ related to $\underline{s} = \underline{s}^*$ is obtained from (13):

$$\frac{1}{K} \begin{pmatrix} z^* & 0 & -X^* z^* & 0 & z^{*2} & 0 \\ -\frac{X^* K}{2b_{l1}} & 0 & \frac{z^{*2}+r^2}{2b_{l1}} & 0 & -\frac{X^* K z^*}{2b_{l1}} & 0 \\ z^* & 0 & X^* z^* & 0 & z^{*2} & 0 \\ \frac{X^* K}{2b_{l1}} & 0 & \frac{z^{*2}+r^2}{2b_{l1}} & 0 & \frac{X^* K z^*}{2b_{l1}} & 0 \\ 0 & -\frac{Y^* K}{2a_{l2}} & \frac{z^{*2}+r^2}{2a_{l2}} & \frac{Y^* K z^*}{2a_{l2}} & 0 & 0 \\ 0 & z^* & -Y^* z^* & -z^{*2} & 0 & 0 \\ 0 & \frac{Y^* K}{2a_{l2}} & \frac{z^{*2}+r^2}{2a_{l2}} & -\frac{Y^* K z^*}{2a_{l2}} & 0 & 0 \\ 0 & z^* & Y^* z^* & -z^{*2} & 0 & 0 \end{pmatrix} \quad (27)$$

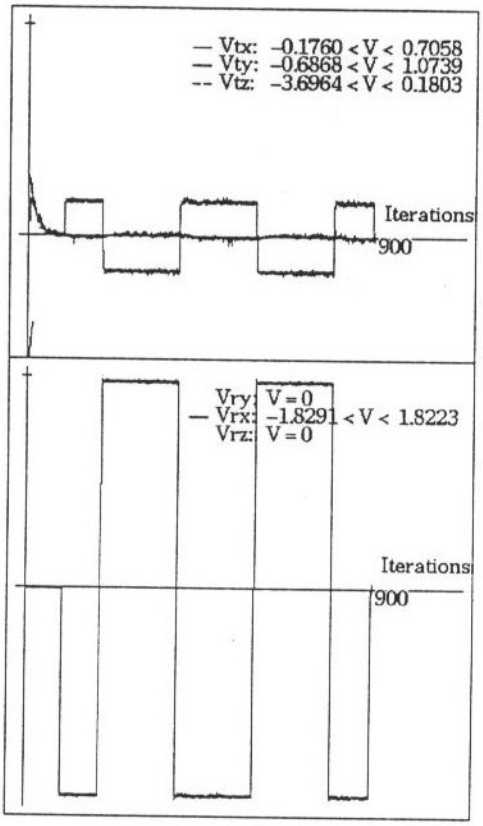

Figure 4: Use of points of discontinuity (with a secondary task)

V. Conclusion

In this paper, we have modelled visual information in a spherical scene case. This modelling establishes a relation between the variation of visual information and the various motions of the visual sensor. Then, we have integrated these works under the *task function approach* which allows the achievement of a positioning robotics task in goods robustness and stability conditions. Finally in our experimental cell, results are presented for the positioning task with respect to a sphere.

We have demonstrated the various advantages of a camera-laser coupling. Nevertheless, this sensor has some constraints. Indeed, this coupling involves some restrictions in the laser stripe projection onto the scene. It is necessary to choose the most favourable situation of the laser stripe in order to achieve a robotics task in conditions of greatest stability. Moreover, a calibration step is essential in order to compute each parameter of a laser plane. The accuracy of a robotics tasks accomplishment will depend on this calibration step. However, a wide field of investigation is still to be studied. It would be interesting to define a methodology in the choice of visual information in order to perfectly control the progress of the robotics task.

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