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A visual servoing approach applied to robotic tasks

Jean-Philippe URBAN, Guy MOTYL, Jean GALLICE

Laboratoire d'Electronique, URA 830 DU CNRS
F 63177 AUBIERE CEDEX

ABSTRACT

We are interested in the design of control systems which work in closed loop with regard to the environment, achieving robotic tasks with the use of vision data. We apply a visual servoing approach to robotic tasks consisting in the positioning of the end effector relatively to a priori known 3D objects.

The robotic configuration is constituted by a CCD camera coupled with one or two laser stripes mounted on the hand of a manipulator.

In order to formalize the problem, we choose the *sensor based control* approach [Espiau87], [Samson90], and applied to visual servoing [Rives87b], [Rives89], [Chaumette90].

We express our approach (camera-light stripe coupling) with this formalism. In our case, the elementary signals are *points of discontinuity*. In order to demonstrate the feasibility of this approach, we implemented the control algorithm in a robotic environment built in our laboratory. We present simulation and experimental results obtained with two positioning tasks. The obtained results thus prove the robustness and the stability of the algorithm.

1) INTRODUCTION

Considering the importance and diversity of the vast field of robotic vision, it is necessary to define exactly the scope of the study depending on the type of considered visual tasks (2D / 3D vision,...), the experimental configuration (static or mobile camera, linked to the end-effector or not, single or multi-camera), the considered visual approach (static vision, dynamic vision) and the nature of robotic control scheme (*static look and move, visual servoing*). Our purpose is to emphasize the potential offered by the use of a single mobile camera mounted on the end-effector of a robot manipulator. Further in this section, we explain our choices concerning the used approaches.

A mobile camera moving in a 3D static scene has the following interests :

* Endowning the camera with the 6 degrees of freedom of a manipulator enables to move around the scene and visualize it from different angles of view [Agin 85].

* A mobile vision system enables to use a *dual control* scheme, for example an extra motion introduced by the control scheme would enable the movement around an obstacle [Rives 87a].

* A mobile camera permits *global vision* as well as *local vision* [King 88].

* An end effector mounted camera can be used to virtually eliminate parallax error as the camera is positioned so that the center of the object lies on the optical axis [Loughlin 83].

A visual sensor mounted on the end-effector of a manipulator has the following interests :

* To formalize the control problem, the effector is the key place to mount the camera. This is because the effector interacts with the environment of the robot and its very motion defines the realization of a task.This means that one has to extract from the vision sensor the interesting data necessary to control the motion of the effector.

* The use of on-board vision sensors as an end-effector relative position measuring system gives a mean to overcome the limitations due to inexact arm modelling, if the rigid camera-effector transformation is known.

* This particular configuration permits to formalize the control problem in a new space, the *task space*, since the vision sensor produces relative position data in relation to the task. This is referenced as *sensor-based-control* [Espiau87].

Visual servoing and camera-laser coupling :

A visual servoing approach involves a compatibility between the measuring frequency of the visual signals of the camera and the sampling rate of the robot controller. In spite of using low level visual signals (points, lines, ellipses,...) the use of specialised hardware will be necessary to extract them in real time (i. e. at video rate).

For this reason, we couple rigidly one or two laser stripes to the camera. The use of rigid *camera-light stripe* coupling undergoes specific projection restrictions but the image processing is simplified by reducing the images to well detected segments of lines resulting of the projection of light stripes on the object. The kind of tasks we are able to realize with this approach are those needing the control of the geometrical interactions between the sensor and the environment. This can be expressed as the control of the relative location between a sensor linked frame and a scene linked frame (e.g. homing, vehicle guiding,...). We are particularly interested in tasks where the visual servoing of the camera consists in centering an object in the image frame. In the past, we tested this technique using an intuitive approach on several industrial tasks in automotive industry : - positioning of the car door on a vehicle - positioning the end effector tool over a battery - positioning the robot arm for the mounting of the wind screen. Respecting the restrictive laser-camera coupling projection conditions, the visual signals were intuitively chosen so as to control directly the corresponding axes. This approach is possible and efficient for the control of two degrees of freedom but not adequate to solve the problem more generally. Therefore we express our visual servoing approach using a camera-light stripe coupling with the general formalism of *sensor based control* [Espiau87], [Samson90], and applied to visual servoing [Rives87b], [Rives89], [Chaumette90].

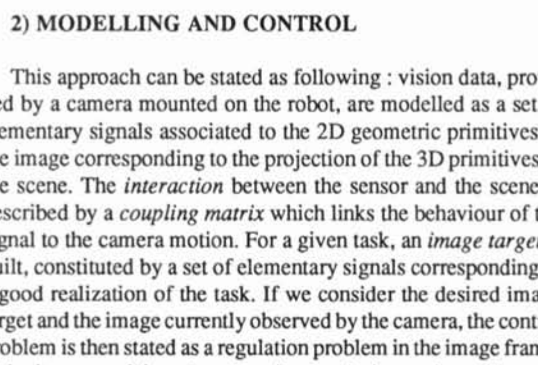
2) MODELLING AND CONTROL

This approach can be stated as following : vision data, provided by a camera mounted on the robot, are modelled as a set of elementary signals 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* which links the behaviour of the signal to the camera motion. For a given task, an *image target* is built, constituted by a set of elementary signals corresponding to a good realization of the task. If we consider the desired image target and the image currently observed by the camera, the control problem is then stated as a regulation problem in the image frame. Velocity control based on *gradient* techniques then allows to perform correctly the task with good convergence properties.

2.1) Modelling the visual signals

We use the classical pinhole approximation to model the perspective geometry of the sensor, assuming (without loss of generality) the focal length equal to unity. At each time, a point $P=(X, Y, Z)^T$, linked to an object, projects onto the image plane as a point $p = (x, y)^T$ with :

$x = X/Z \; ; \; y = Y/Z$ (1)



Notations

We assume that the motion of the sensor, mounted on the end effector of a manipulator, is fully controlable and can be characterized by the velocity screw $\xi_c = (V_c, \Omega_c)^T$, where V_c and Ω_c represent respectively its translational and rotational velocities. Due to the motion of sensor and objects, the point P moves with a relative velocity screw $\xi = (V, \Omega)^T$ with respect to the camera frame by means of :

$P(\dot{X},\dot{Y},\dot{Z}) = V + \Omega \wedge CP$ (2)

By differentiating (1) and using (2), we can derive the well known equation relating optical flow measurement to 3D structure and motion in the scene :

$$\begin{pmatrix} \dot{x} \\ \dot{y} \end{pmatrix} = \mathbf{H}.\zeta \quad (3) \quad \text{with}$$

$$\mathbf{H} = \begin{pmatrix} \frac{1}{Z} & 0 & -\frac{x}{Z} & -xy & (1+x^2) & -y \\ 0 & \frac{1}{Z} & -\frac{y}{Z} & -(1+y^2) & xy & x \end{pmatrix}$$

This equation shows the basic structure of the *interacion* between the vision sensor and its environment. This interaction depends on the inverse of the depth Z of the point expressed in the camera frame, and an a priori knowledge about the environment is needed to know the true value of the interaction. Considering geometrical primitives more complex than points, an important part of the visual servoing problem must be devoted to find a well suited parametrization for each given 3D primitive, and to establish the corresponding interaction matrix H. We refer to [Espiau 90] for the definition of a set of elementary visual signals from low level geometrical primitives like points, lines, circles and spheres.

In the present case of a *camera-laser* sensor using *points of discontinuities* as elementary signals, we have to find the appropriate interaction matrixes since the model of the used sensor is more complex than the classical pinhole approximation model. In the next section we will calculate the interaction matrix for two positioning tasks.

2.2) Control

The control aspect of the problem is drawn from the results obtained by B. Espiau and C. Samson on *rigid manipulator control* and *sensor based control*. F. Chaumette and P. Rives applied this approach to vision, using the elementary visual signals in a robust control scheme based on a task function approach.

The robotic task is stated in terms of reaching a particular configuration (target image), which is constituted of a set of features in the image frame. For a given robotic task, we have to choose a set of visual signals which allows to perform the task. Then, we define a task vector e(t) such that $e(t) = s(t) - s^*$, where s^* can be considered as a reference image target to be reached in the image frame, and s(t) as the visual signals currently observed by the camera. Considering the control problem as an output regulation problem, we can assume that the concerned task is perfectly achieved if $e(t) = 0$. We focus on the robustness with respect to the uncertainties by using a gradient-based approach : in this approach, it is possible to define an error function ($=\|e(t)\|$) and to express the regulation problem as a minimization problem. Under these assumptions, we may choose as camera control vector expressed in the camera frame :

$\xi_c = \mu\, C\, e(t)$ (4)

where $\mu > 0$ and C is a constant matrix. We have :

$e = s = H \,.\, \xi$ (5)

with $\xi = -\xi_c$ and, from eq. (4), we obtain :

$e = -\mu\, H \,.\, C \,.\, e(t)$ (6)

An exponential convergence will be ensured under the following sufficient condition [Samson 87] :

$H \,.\, C > 0 \,, \forall t$ (7)

A good and simple way to try to ensure this matrix positivity is to enforce $H \,.\, C = I_p$ (identity matrix) for the equilibrium position $s = s^*$. If H is rectangular ($p \pm 6$ in our case), C may be chosen as the pseudo-inverse of H.

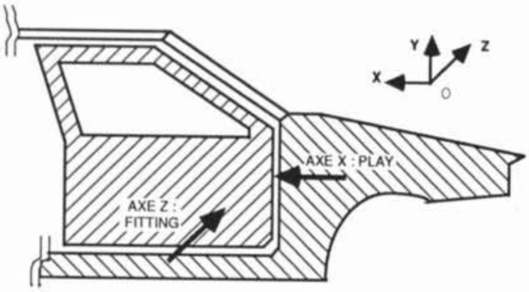
3) EXPERIMENTAL RESULTS

We have validated this approach both in simulation and in an experimental cell defined and built in our laboratory, taking into account the needs required to carry out a real-time sensor motor cooperation.

We describe simulation and experimental results obtained with two positioning tasks[Urban90] :

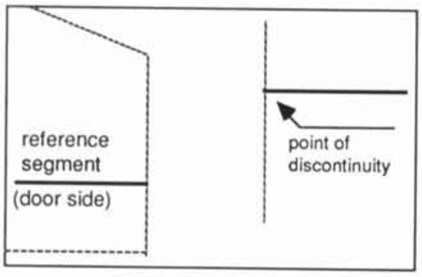
3.1) Task 1 : positioning of the car door on a vehicle

This task consists in fitting the door to the wing and adjusting the clearance between the door and the wing. Two axis have to be controlled : Z axis : fitting ; X axis : play.



Axes to control

The door is carried by the tool at a distance of 300mm from the on-board vision system. The laser stripe, projected in the Ox axis, produces two light segments : the first, projected onto the door, will be the reference segment, and the second will give the useful information for control.



Laser segments in the image frame

Two elementary signals, the coordinates of the point of discontinuity, will be used. In this case, the restrictive projection conditions are the following :

Point 1: the object plane is parallel to the image plane;

Point 2: the image frame axes (Ox, Oy) are parallel to the scene frame axes (OX,OY) ;

Point 3: the camera-laser coupling is such that the projection of the stripe is parallel to the Ox axis in the image.

Therefore :

* a Z axis motion of the end effector will affect the stripe projection in the y axis ;

* also, an X axis motion enables to position correctly the break of the stripe at the discontinuity in the x axis ;

* Rotations are not allowed so as to respect point 1and point 2 (point 1 : no Ω_x, Ω_y rotations ; point 2 : no Ω_z rotation).

The non respect of these conditions makes the problem ambiguous.

Let α be the angle between the camera axis and the laser stripe.The rigid laser-camera coupling is such that when the object plane is at the desired distance Z*, the observed 2D line will be on $y = 0$.

Equations (1) remain applicable $x = X/Z$; $y = Y/Z$

moreover, in this case $Y = -\,tg\,\alpha\,.\,(Z - Z^*)$ (8)

so $x = X/Z$

and $y = -\,tg\,\alpha\,.\,(1 - Z^*/Z)$ (9)

Differenciating equations (9) and using equation (2), we obtain the new interaction matrix (and with Z* = Z) :

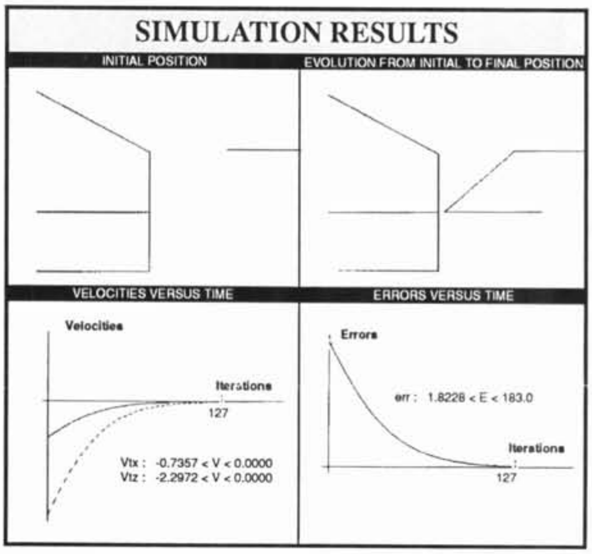
$$\begin{pmatrix} \dot{x} \\ \dot{y} \end{pmatrix} = \mathbf{H}.\zeta \quad (3)$$

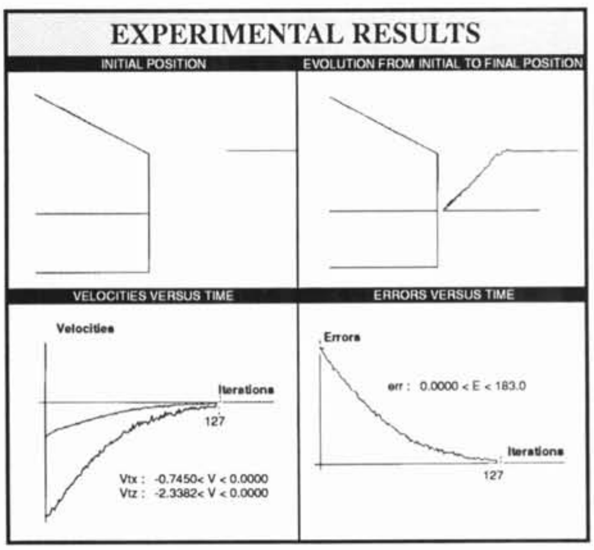
with

$$\mathbf{H} = \begin{pmatrix} \frac{1}{Z} & 0 & -\frac{x}{Z} & -xy & (1+x^2) & -y \\ 0 & 0 & -\frac{tg\,\alpha}{Z} & 0 & x.tg\,\alpha & 0 \end{pmatrix}$$

Using only one point of discontinuity, the control matrix C is reduced to a 2*2 square matrix corresponding to both axes to control (x and z translations).

Hereafter we show some simulation and real experimental results.The two top windows present the target as seen by the camera. The window on the left corresponds to the initial position and the window on the right to the evolution in time from the initial position to the final one.The two bottom windows show the behaviour of each component of the control vector C during the visual servoing (left window) and the evolution of the error || e(t) || (right window). For comparison, both results are given for the same initial image.

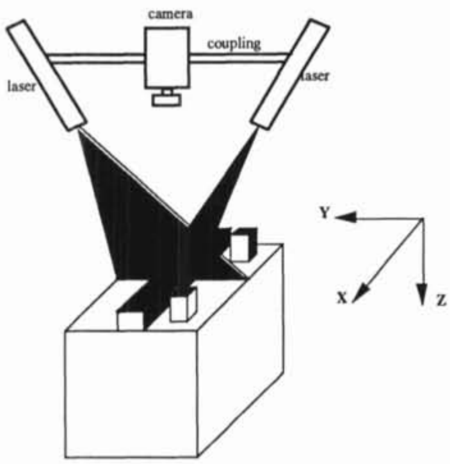




The convergence to the desired image target is performed and the behaviour of the real system is extremely close to the one expected by the simulation.

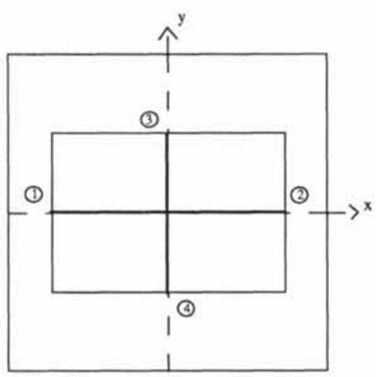
3.2) <u>Task 2 : positioning the end effector tool over a vehicle battery</u>

In this case, two laser stripes are rigidly coupled to the camera. The image produced by the projection of laser stripes onto the battery will be limited to two line segments : one segment in the x axis and the second in the y axis.



From the perceived image, we extract four points of discontinuity corresponding to the battery edges. The coordinates of these points will be the elementary signals used for control.

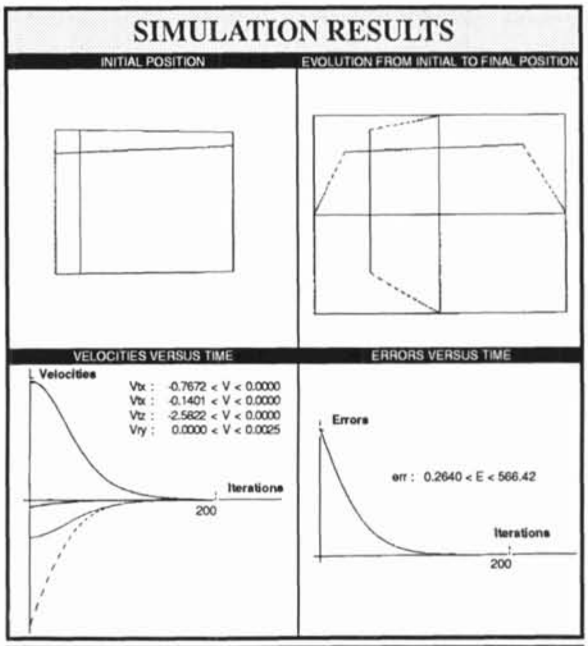
The task consists in centering the tool over the battery at a distance of 300mm, assuming that the dimensions of the battery are known. In the image frame, the task will be achieved when both segments are respectively on x = 0 and y = 0.

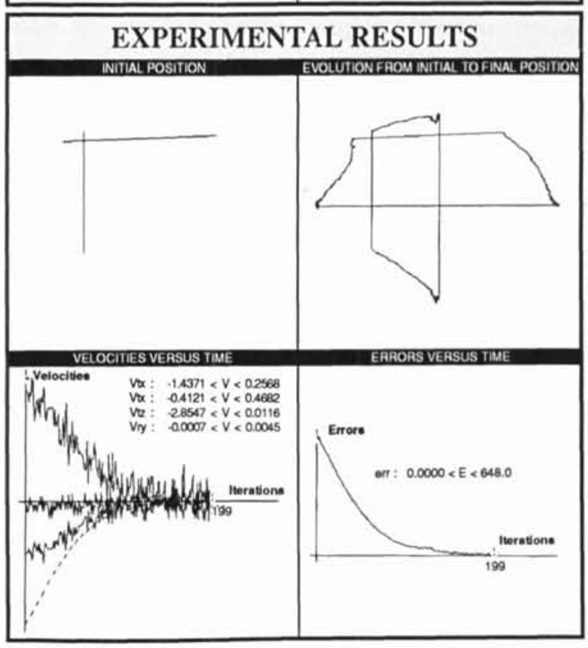


The interaction matrix is obtained in the same manner as previously :

$$H = \begin{pmatrix} \frac{1}{Z} & 0 & \frac{-x_1}{Z} & -x_1 y_1 & (1+x_1^2) & -y_1 \\ 0 & 0 & \frac{-tg\alpha_x}{Z} & 0 & x_1 tg\alpha_x & 0 \\ \frac{1}{Z} & 0 & \frac{-x_2}{Z} & -x_2 y_2 & (1+x_2^2) & -y_2 \\ 0 & 0 & \frac{-tg\alpha_x}{Z} & 0 & x_2 tg\alpha_x & 0 \\ 0 & 0 & \frac{+tg\alpha_y}{Z} & y_3 tg\alpha_y & 0 & 0 \\ 0 & \frac{1}{Z} & \frac{-y_3}{Z} & -(1+y_3^2) & +x_3 y_3 & +x_3 \\ 0 & 0 & \frac{+tg\alpha_y}{Z} & y_4 tg\alpha_y & 0 & 0 \\ 0 & \frac{1}{Z} & \frac{-y_4}{Z} & -(1+y_4^2) & +x_4 y_4 & +x_4 \end{pmatrix}$$

These 8 elementary signals permits to control up to 5 degrees of freedom and thus, the restrictive projection conditions disappear. There remains a lack of information to control the Z rotation : the control matrix (the pseudo-inverse of the interaction matrix) can not be calculated because all elements of one column of the matrix are zeros. To solve this ambiguity it would be necessary to introduce other elementary signals (e.g. the distance between two points of discontinuity). Next we show some simulation and the corresponding experimental results.





Note that the stability of the control scheme, expressed by the amount of noice present in the velocities (cf figure), is directly linked to the camera-laser angle α (in our case $\alpha = 14°$).

Furthermore the behaviour of the real system is extremely close to the one expected by the simulation results.

4) CONCLUSION

The different experimental results thus obtained, in simulation as well as in the real system, prove the robustness and the stability of the algorithm. The coordinates of points of discontinuity as elementary signals in a camera-laser coupling configuration is interesting, but to use the image information at its most, it seems promising to also introduce projected line segment primitives in the control scheme. In nearby future, we plan to modelize such primitives in order to realize more complex visual tasks.

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