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VISUAL SERVO CONTROL OF INDUSTRIAL ROBOT MANIPULATOR

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Abstract: This paper presents an image-based visual servo controller for an industrial robot. The simple structure controller is based on a transposed Jacobian which feeds back directly the image feature errors and the joint velocities. Under these hypotheses, the control algorithm does not need to use the inverse kinematics and the inverse jacobian matrix. Experimental results in two different industrial robots are also presented to illustrate the controller's performance. *Copyright © 2002 IFAC*

Keywords: Robotics, control, robot vision, image processing, target tracking, dynamics.

1. INTRODUCTION

Nowadays, the great majority of robot population operates in factories where the work environment is structured and previously well-known. The application of a robot to carry out a certain task depends, in a high percentage, on the previously knowledge about the work environment and object placement. This limitation is due to inherent lack of sensory capability in contemporary commercial industrial robots. It has been long recognized that sensor integration is fundamental to increase the versatility and application domain of robots. One of these sensor systems is Computer Vision.

Computer vision is a useful robotic sensor since it mimics the human sense of vision and allows for non contact measurement of the work environment. Industrial robot controllers with fully integrated vision systems are now available from a large number of suppliers. In these systems, visual sensing and manipulation are typically integrated in an open-loop fashion, looking then moving. The precision of the resulting operation depends directly on the accuracy of the visual sensor and the robot end-effector.

An alternative solution for the position and motion control of an industrial manipulator evolved in unstructured enviroments is to use the visual information in a feedback loop. This robot control strategy is called visual servo control or visual servoing.

A visual servo controller for camera in hand scara robot is presented in this paper. The controller is of a simple structure based on a transpose Jacobian (Takegaki and Arimoto, 1981) which feeds back directly the image feature errors and the joint velocities. This controller has been tested experimentally on two industrial robots (BOSCH SR-800, whose original control structure has been modified and Mitsubishi PA-10).

This paper continues the work originally presented in R. Kelly, *et al* (2000).

2. DYNAMIC MODEL OF INDUSTRIAL ROBOT

2.1. Manipulator model.

The first robotic system considered in this paper is BOSCH SR-800 which has two degrees of freedom in the plane of the figure 1 . Where m_1 is the mass of the link 1, l_1 is the length of the link 1, I_1 is the inertia of the link 1, r_1 is the link 1 center of mass, q_1 is the joint position of the link 1, m_2 is the mass of the link 2, l_2 is the length of the link 2, I_2 is the inertia of the link 2, r_2 is the link 2 center of mass, q_2 is the joint position of the link 2. In the absence of friction or other disturbances, the robot manipulator dynamics can be described as it is shown in this equation:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = t \qquad (1)$$

where:

$\mathbf{q} \in \Re^n$ vector of joint displacements.

$\dot{\mathbf{q}} \in \Re^n$ vector of joint velocities.

$t \in \Re^n$ vector of applied joint torques.

$\mathbf{C(q, \dot{q})} \in \Re^{nxn}$ vector of centripetal and Coriolis torques.

$\mathbf{M(q)} \in \Re^{nxn}$ symmetric positive definite manipulator inertia matrix.

$\mathbf{g(q)} \in \Re^n$ vector of gravitational torques.

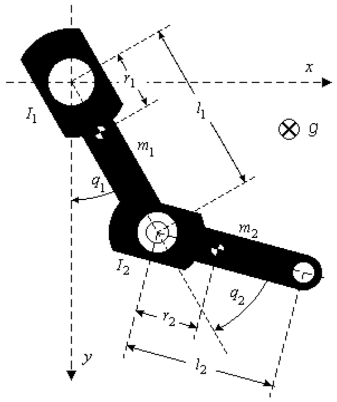


Fig. 1. 2 dof Scara Robot (BOSCH SR-800)

The robot parameters(BOSCH SR-800) were obtained by identification. (Mamani G., 2000)

The second robotic system considered in this paper is Mitsubishi PA-10 which has seven degrees of freedom. In experimentation only two dof, 2^{nd} and 4^{th} , have been considered. So the robot movement is restricted to the plane X_0Z_0(Fig 2 and Fig4).

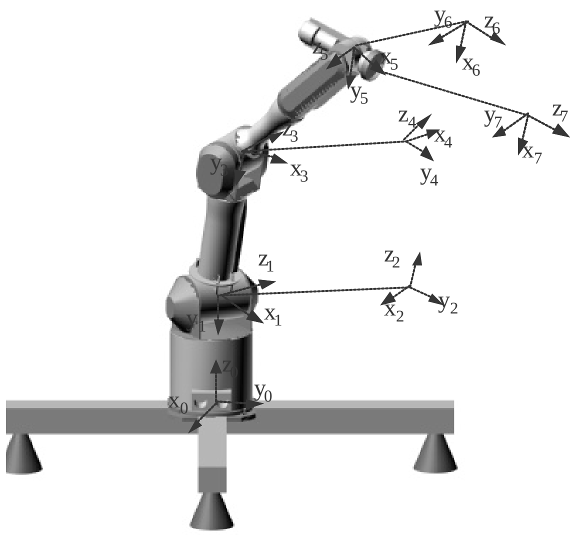


Fig. 2. Mitsubishi PA-10.

2.2 Motors Model

Let us consider the electric outline of the DC motor with gearbox shown in the figure 3.

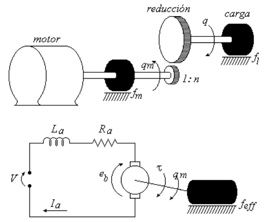


Fig. 3. Electrical and mechanical motor model.

The electrical pattern of the motor can be described by the following equations:

$$t_m = K_a \cdot I_a \qquad (2)$$

$$V = R_a \cdot I_a + L_a \cdot \frac{dI_a}{dt} + K_b \cdot \dot{q} \qquad (3)$$

$$q_m = R \cdot q \qquad (4)$$

where t_m is the torque in the motor axis, K_a is the motor-couple constant, I_a is the armature current, V is the armature voltage, R_a is the resistance of armature of the motor, L_a is the inductance of armature, K_b is the electromotive constant, $\dot{q}$ is joint velocity, R is the gearbox ratio, q_m is the joint position of the axis motor, q is the joint position of the axis of the load.

The *movement equation* for the system is:

$$J_m \cdot \ddot{q}_m = t_m - f_m(\dot{q}_m, t_m) - \frac{t}{R} \qquad (5)$$

where J_m is the inertia of the rotor, $\ddot{q}_m$ is the acceleration of the motor axis , $\dot{q}_m$ is the velocity of the motor axis, $f_m(\dot{q}_m, t_m)$ is the friction of the rotor in its bearings, t is the load torque after the game of engagements on the axis of the load.

The motor electrical model working in this way can be represented by the following equation

$$I.\ddot{q} + F.\dot{q} + Dn.t = K.u \qquad (6)$$

3. TRANSPOSED JACOBIAN CONTROLLER WITH VISUAL FEEDBACK

A visual servo controller is presented with the configuration camera in hand, so that the camera moves solidary to the robot´s axes. The proposed image based visual servo controller relies on the control philosophy of the Transposed Jacobian, (Takegaki *et al*., 1981). This controller has a simple structure based on the direct feedback of image feature errors, joint velocities and compensation of the gravity. The controller´s algorithm must be adapted for its implementation in an industrial robot.

3.1. Image features

An image feature is generally defined as any measurable relationship in an image and examples include moments, relationships between regions or vertices, polygon face areas, or local intensity patterns. The most commonly used are the coordinates of a feature point or region centroid, as in this paper (Hashimoto K. *et al*., 1993), (Papanikolopoulos *et al*., 1993), (Espiau B. *et al*., 1992).

An object feature point with coordinates ${}^{c}p_o = [{}^{c}p_x \; {}^{c}p_y \; {}^{c}p_z]$ in the camera frame projects onto a point on the image plane, with image coordinates $[u \quad v]^T \in R^2$. The position of an object feature point in the image will be referred to as an image feature point.

3.2. Control Problem Formulation

The robot task is specified in the image plane in terms of the image feature values corresponding to the relative robot and object positions. Let us denote x_d as the *desired image feature* vector which is assumed to be constant. For some tasks, the desired feature vector can be obtained directly in the image feature space.

The control problem is to design a controller which computes the applied torques to move the robot in such a way that the actual image features reach the prescribed desired ones. The *image feature error* defined as $\tilde{x} = x_d - x$ may be calculated at every measurement time and used to drive the robot in a direction which decreases the error. Therefore, the control aim is to ensure that

$$\lim_{t \to 0} \tilde{x}(t) = 0$$

with the error of initial characteristics and the joint velocities sufficiently small.

The depth ${}^{c}p_z$,that it is the distance from the camera to the object, is supposed to be known.

3.3 Control Law

The proposed control law (Nasisi, 1998) (Kelly *et al*., 2000) is given by.

$$t = J(q,x,{}^{c}p_z)^T K_p \tilde{x} - K_v \dot{q} + g(q) \qquad (7)$$

where $\mathbf{K_p} \in \Re^{2p \times 2p}$ and $\mathbf{K_v} \in \Re^{n \times n}$ are the symmetric positive-definite proportional and derivative matrices which are chosen by the designer.

It is worth noticing that the controller uses directly the feature error vector $\tilde{x}$ which is the difference between the desired feature vector and the actual one expressed in the image coordinate frame. The controller also requires the measurement of the joint position $\mathbf{q}$ and velocity $\dot{\mathbf{q}}$, the knowledge of the Jacobian matrix, $\boldsymbol{J(q,x,p_z)}$ and the gravitational torque vector $\mathbf{g(q)}$. However, the solution of the inverse image and kinematics are obviated.

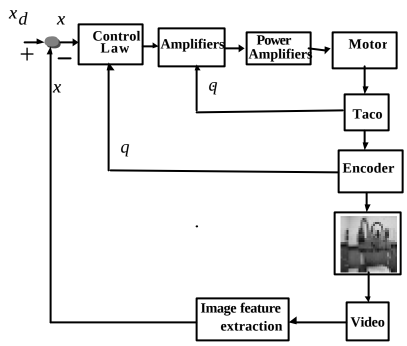


Fig. 4 Block diagram of image based visual servoing system.

The resulting jacobian matrix is defined as the product of the image jacobian and analytical jacobian of the manipulator (Sciavicco and Siciliano, 1996) , (Kelly *et al*., 2000).

$$J(q,x,p_z) = J_I(x,p_z) J_{AR}(q) \qquad (8)$$

4. EXPERIMENTAL RESULTS

The experimentation of the visual servo control was carried out with an industrial robotic SCARA SR-800 manipulator, annulling the 3rd and 4th dof and with another industrial manipulator Mitsubishi PA-10, considering only the 2nd and 4th dof.

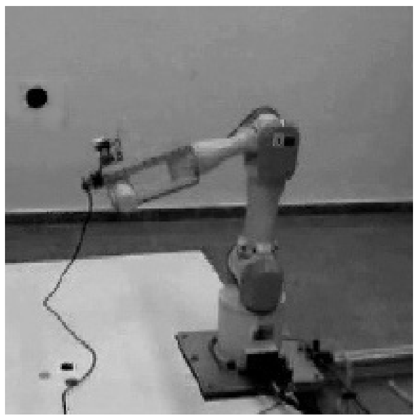


Fig. 5. One of the Experimental equipment set-up (Mitsubishi PA-10) at Miguel Hernandez University.

4.1. Bosch SR-800

Each joint has an analog velocity feedback loop conforming an internal speed controller. The implementation must be modified in order to respect this characteristic in the robotic system.

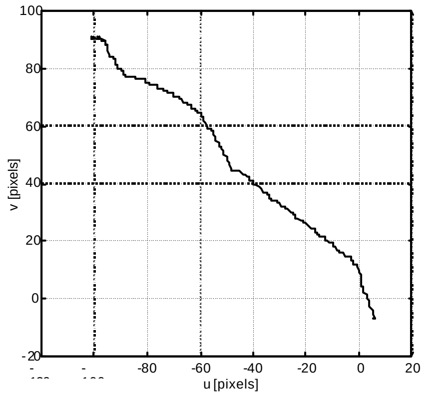
Experimental results are shown in Fig. 6-8. A punctual object which was a black 100 pixel-diameter circle was considered.

The controller parameters were selected as:

$$K_p = \begin{bmatrix} 1\times10^{-5} & 0 \\ 0 & 1\times10^{-5} \end{bmatrix} \left[Nm / pixeles^2 \right]$$

$$K_v = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \left[Nm / pixeles^2 \right]$$

Experimentation



Simulation

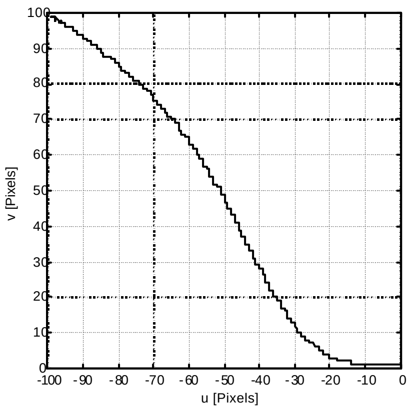
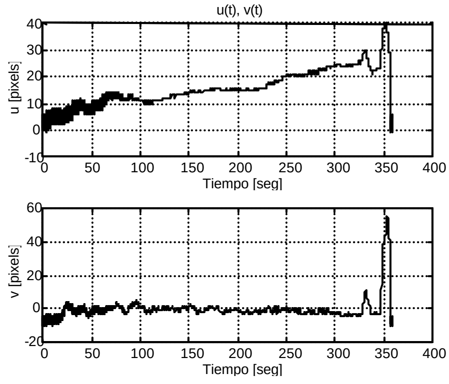
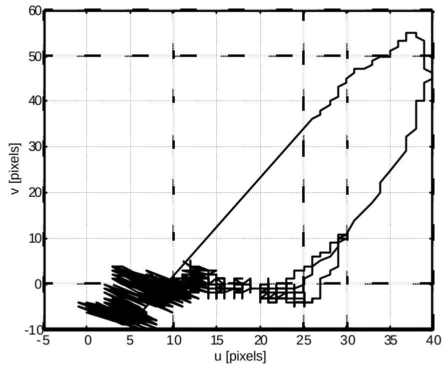


Fig. 6. Experiment 1: Comparison with Simulation. Feature position trajectory in image plane

The experiment consisted on taking the characteristic point in the image from the initial position ($x(0) = [0 \quad 0]^T$), to the desired position ($x_d(0) = [100 \quad -100]^T$) what corresponds to the desired movement of the manipulator related to the physical object. The positions in the image plane are given in pixels. Fig. 6 represents the results of simulation and experimentation of the trajectories of the feature point on the image. Experimental results with the same controller where the object has a certain motion have been carried out. In Fig. 7, Fig. 8 the results of tracking are shown. As both figures shown, the controller is able to track the object with enough accuracy.



(a).



(b)

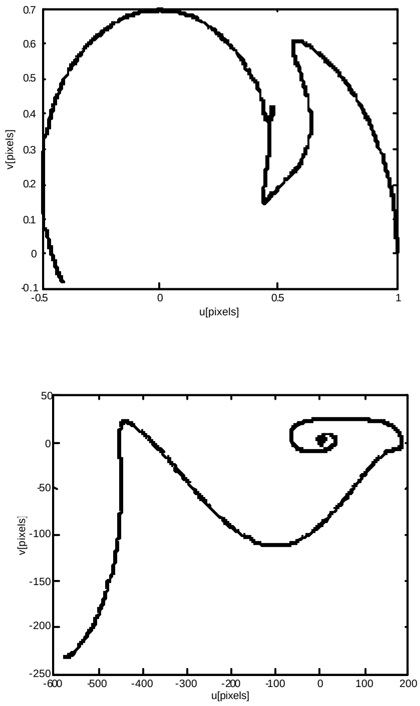
Fig. 7. Experiment 2: Tracking. Experimentation (a). Time evolution of the camera coordinates (b). Feature position trajectory in image plane.

4.1. Mitsubishi PA-10

The Mitsubishi PA-10 robot with a camera rigdly mounted on the robot end-effector(eye-in-hand configuration) was used.

In figure 9, a block diagram of image-based visual servoing system is shown. In this schema, an error function between the current location of the feature points and the desired location is defined. Then we have a proportional matrix gain Kp2x2 (symmetric positive-defined matrix) which is chosen by the designer.

The experiment consisted on taking the feature point in the image from the initial position ($x(0) = [-113 \quad 91]^T$), to the desired position ($x_d(0) = [0 \quad 0]^T$) what corresponds to the desired movement of the manipulator related to the physical object. The positions in the image plane are given in pixels. As a feature point a centroid of punctual object which was a black circle was considered.



(b)

Fig.8. Experiment 2: Tracking. Simulation(a). Path of the camera in the robot workplane (b) Feature position trajectory in image plane

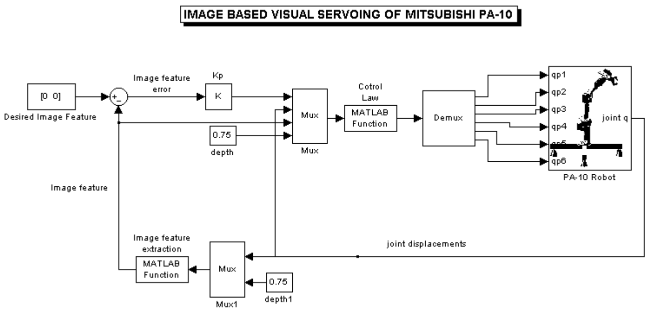


Fig. 9. Block diagram of image-based visual servoing system (Mitsubishi PA-10).

Fig. 10 represents the experimental results of the trajectory of the feature point on the image. The initial and final position of the feature point are considered respect the frame shown in Fig 10:

Initial position: ($x(0) = [-113 \quad 91]^T \approx [279 \; 376]^T$)

Final position: ($x_d(0) = [0 \quad 0]^T \approx [391 \; 287]^T$)

The crontoller's performance is shown in Fig. 11. This figure represents the experimental results of evolution of image feature error.

As Fig. 11-12 shown, the proportional controller, presented in this paper, is capable of placing the camera mounted on the robot in a desired relative position with respect to static object. We have carried out simulations with the same controller where the object has a circular motion. In this case, the system is able to track the object with enough accuracy.

(a)

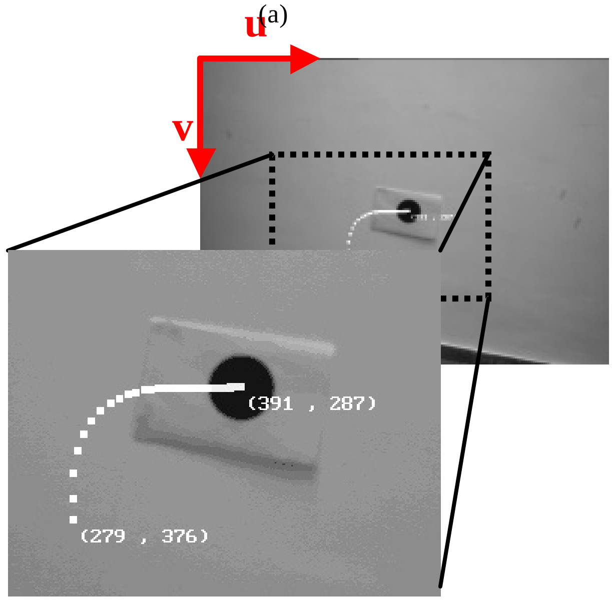


Fig. 10. Experimental results. Trajectory of the feature point on the image.

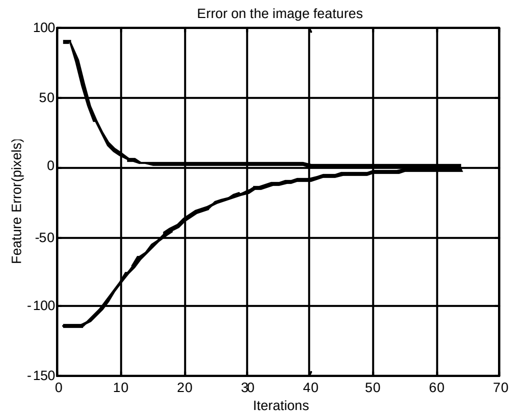


Fig. 11. Evolution of image feature error.

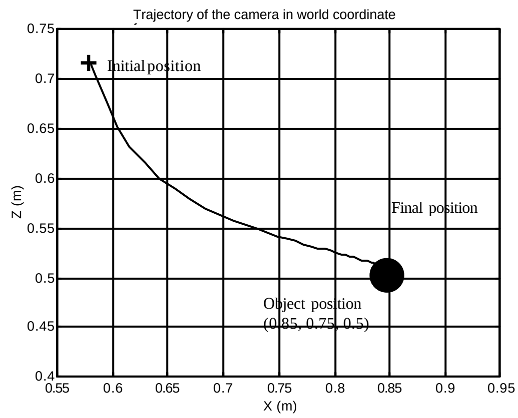


Fig. 12. Trajectory of the camera in world coordinate frame

5. CONCLUSION

A Visual Servo controller for two robotic industrial manipulators, SCARA SR-800 and Mitsubishi PA-10, with camera in hand configuration has been presented. In SCARA SR-800, the controller is of a simple structure based on a transpose Jacobian term plus gravity compensation which feeds back directly the image feature errors and the joint velocities. In Mitsubishi PA-10, the controller is based on an inverse Jacobian. Both controllers are capable of placing the camera mounted on the robot in a desired relative position with respect to a static object. By using the Lyapunov's direct method, the stability of the closed-loop system can be demostrated. It should be emphasized that the full non-linear robot dynamics has been included in the analysis. Local asymptotic stability can be achieved under weak assumptions on the Jacobian by invoking the Krasovskii–LaSalle's theorem. Experimental results with a two-degree-of-freedom industrial arms, using one feature point, were presented to illustrate the control system stability and performance. Also some simulation an experimental results of tracking has been presented.

The exposed theoretical results were corroborated through the comparison of the experimental and simulation results.

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