CAMERA CONFIGURATIONS OF A VISUAL SERVOING SETUP, FOR A 2 DOF PLANAR ROBOT

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Abstract: This paper presents a study of three different camera configurations, for a 2 dof planar robot, comparing their behavior based on the singularities of the jacobian used in the control law. The camera configurations used were: eye-to-hand; eye-in-hand with the camera looking respectively in front and down. Two image features, coordinates of a point, from the target were used. Plots representing jacobian singularities, within the joint limits, are presented for a known target position. Some conclusions are also drawn when the target position is unknown. Simulation results for 2D Visual Servoing are presented, to show the behavior of the servoing in the three camera configurations. Copyright © 2003 IFAC

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1. INTRODUCTION

In this paper we control, based on 2D Visual Servoing and under different camera configurations, a 2 dof planar robotic manipulator. The robot in use was constructed at Instituto Superior Técnico (Martins and Sá da Costa, 1999; Baptista, et al, 2001), Mechanical Engineering Department, Robotics and Automation Laboratory.

Planar robots are widely spread in the industry, two of their most important characteristics being speed and precision. This type of robotic structure can easily evolve to a SCARA robot, used in vertical assembly tasks, palletizing, etc.

The first objective of this work is to study the planar robotic manipulator under 2D Visual Servoing, for three different camera configurations: eye-to-hand; eye-in-hand with the camera looking in front and down. The second objective is to find the singularities of the jacobian, relating the image features velocity to the joint velocity, in order to avoid them in path planning schemes.

The robot should move from an initial to a final position, with the control taking place in the image features space. The control law and the control structure used to accomplish these objectives are presented in section 2. The planar robot manipulator is presented in section 3. The three camera configurations and the singularities of the jacobian are presented in sections 4 and 5, respectively. The simulation results are presented in section 6. Some conclusions of this work are exposed in section 7.

2. VISUAL SERVOING

Machine Vision and Robotics can be used together to control a robot manipulator. This type of control, defined as Visual Servoing, uses visual information from the work environment to control a robot manipulator performing a task.

The visual information can be obtained by two ways: using direct information from the image (2D visual servoing); or using 3D information of the object from the image(s) (3D visual servoing). The second case needs an on-line processing for pose estimation. A good explanation of the differences is done in (Hutchinson, et al., 1996). Combining the previous approaches (Malis, et al, 1999) have proposed the 2½D Visual Servoing, nowadays also called Hybrid Visual Servoing. In this paper only 2D Visual Servoing is used.
In this paper, the needed visual/image features to move the robot manipulator are the coordinates of a point. It is necessary to define: a 3D point, \( P \); an image features vector, \( s \); a desired image features vector, \( s^* \); an error vector, \( e \).

\[
P = \begin{bmatrix} X & Y & Z \end{bmatrix}^T \quad (1)
\]

\[
m = \begin{bmatrix} x/Z & y/Z & 1 \end{bmatrix}^T = \begin{bmatrix} x & y \end{bmatrix} \quad (2)
\]

\[
s = \begin{bmatrix} p_1 & \ldots & p_k & \ldots & p_N \end{bmatrix} \quad (3)
\]

\[
s^* = \begin{bmatrix} p_1^* & \ldots & p_k^* & \ldots & p_N^* \end{bmatrix} \quad (4)
\]

\[
e = s - s^* \quad (5)
\]

where, \( N \) is the number of image features.

Since the robotic manipulator used has 2 dof to be controlled, two features are only needed to perform the control. The image features used are the coordinates \( x \) and \( y \) of one image point. The global control architecture is as shown on fig. 1, where the robot block has implemented a PD control law, with the joint velocities as input.

![Fig. 1 Visual Servoing Control Architecture](image)

Following the approach to Visual Servoing made in (Espiau, et al., 1992), to obtain a “good control” it is necessary to minimize a function \( f(s) \):

\[
f(s) = \frac{1}{2} \left| s - s^* \right|^2 \quad (6)
\]

and when the desired image features are obtained: \( e = 0 \).

Considering \( r_c \), the pose of the end-effector (translation and rotation) in the world frame, and \( r_v \), the pose of the camera in the world frame, which are dependent on the robot joint variables \( q \), it is then necessary to find a robot configuration that minimize \( f(s) \):

\[
\min_q f(q) \quad (7)
\]

The function \( f(s) \), reaches a minimum when its first derivate goes to zero, so using equation (7):

\[
\frac{\partial f}{\partial s} \frac{\partial s}{\partial r_c} \frac{\partial r_c}{\partial r_c} = 0 \quad (8)
\]

\[
\frac{\partial s}{\partial r_c} = J_r(x,y,Z), \text{ is the image jacobian,}
\]

\[
s = J_r(x,y,Z) \cdot \dot{r}_c \quad (9)
\]

defined using the pin-hole camera model and a 2D point as the image feature.

\[
J_r(x,y,Z) = \begin{bmatrix} 1 & 0 & x \cdot y & -1 + x^2 & y \\ 0 & -\frac{1}{Z} & y & 1 + y^2 & -x \cdot y & -x \end{bmatrix} \quad (10)
\]

\[
\frac{\dot{r}_c}{\partial r_c} \cdot W_r, \text{ is the transformation between the camera and end-effector frames.}
\]

\[
\dot{r}_c = J_r(q) \cdot \dot{q} \quad (13)
\]

\[
J_r(q) = \begin{bmatrix} l_1 \cdot \sin(q_1) & l_2 + l_1 \cdot \cos(q_1) & 0 & 0 & 0 & 1 \\ 0 & l_2 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (14)
\]

If the previous jacobians are not singular the solution to the minimization problem is when \( e = 0 \) and if at the desired position the object velocity is zero, i.e., \( \dot{s} = 0 \):

\[
\dot{e} = \ddot{s} - \dot{s}^* = \frac{\partial s}{\partial r_c} \frac{\partial r_c}{\partial r_c} \frac{\partial r_c}{\partial q} \cdot \dot{q} \quad (15)
\]

As in (Espiau, et al, 1992), we specify an exponential decayment of the image features error vector, during the servoing, by the following equation:

\[
\dot{e} = -\lambda \cdot e \quad (16)
\]

Finally, from equations (15) and (16), we reach the control law:

\[
\dot{q} = -\lambda \cdot J^{-1}(x,y,Z,q) \cdot (s - s^*) \quad (17)
\]

where \( J \) is the total jacobian, that from now on will be named only the jacobian:

\[
J(x,y,Z,q) = J_r(x,y,Z) \cdot W_r \cdot J_s(q) \quad (18)
\]

Since we have the same number of image features and robot joint coordinates, \( \dim(s) = \dim(q) \), \( J \) is a square matrix and \( J^{-1} \) can be computed at each iteration of the servoing, video rate. In the case of using redundant features, \( \dim(s) > \dim(q) \), we need to calculate the jacobian pseudo-inverse.

According to (Espiau, et al, 1992), in closed loop, the image features error will decrease if equation (19) is satisfied and if the jacobian is non-singular, and \( \dim(s) = \dim(q) \).

\[
J \cdot J^{-1} > 0 \quad (19)
\]
3. THE 2 DOF PLANAR ROBOT MANIPULATOR

A planar robotic manipulator of two degrees of freedom, constructed at the Mechanical Engineering Department in Instituto Superior Técnico, (Martins and Sá da Costa, 1999; Baptista, et al, 2001), was modeled in (Gonçalves, 2001) to implement visual servoing algorithms. The robot has two links $l_1 = 0.32\text{mm}$ and $l_2 = 0.23\text{mm}$.

![Fig. 2 Planar Robotic Manipulator, with camera-in-hand looking down.](image)

4. CAMERA CONFIGURATIONS

Visual Servoing typically uses one of two camera configurations: eye-in-hand, or eye-to-hand (Hutchinson, et al, 1996). It is also possible to combine the previous configurations. Eye-in-hand means that the camera is mounted in the end-effector, and eye-to-hand means that the camera is fixed in the workspace, looking the robot and the target. In this section, the two camera configurations are presented, including two variations on the eye-in-hand scheme.

4.1 Eye-to-Hand Setup.

In fig. 3 are presented all the frames in the eye-to-hand setup: the world(o), the end-effector(e), the camera(c), the object(obj).

![Fig. 3: Eye-to-hand setup](image)

The robot jacobian, $\mathbf{J}_r$, (6×2), defined in (13), and the homogeneous transformation from the world(o) frame to the end-effector(e) frame, $\mathbf{T}_e$, can be obtained using classical robotic techniques (Sciavicco and Siciliano, 2000). The workspace of the robot is on a horizontal plane (2D motion), and defined by the joint limits [-110º ; 110º] for each of the two 2 dof of the robot.

$$\mathbf{T}_e = \begin{bmatrix} 1 & 0 & 0 & 0.23 \\ 0 & -1 & 0 & -0.3 \\ 0 & 0 & -1 & 1.0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

4.2 Eye-in-Hand Setup.

Camera looking in front

In fig. 4 are presented all the frames in the eye-in-hand setup, camera looking “in front”: the world(o), the end-effector(e), the camera(c), the target(t). The origin of frames c and e are coincident, but rotated as shown in $\mathbf{T}_e$ above.

![Fig. 4: Eye-in-hand setup, camera looking “in front”.](image)

The matrix $\mathbf{W}_c$ is computed using equation (12), leading to a (6×6) matrix depending on the end-effector position and orientation, i.e., on the joint angles. In this configuration, the end-effector (target) should move to a desired position, defined by $\mathbf{T}_{obj}$.

Camera looking down

In fig. 5 are presented all the frames in the eye-in-hand setup, camera looking “down”: the world(o), the end-effector(e), the camera(c), the target(t). The origin of frames c and e are coincident, but rotated as shown in $\mathbf{T}_e$ above.

![Fig. 5: Eye-in-hand setup, camera looking “down”.](image)
The matrix $cW_e$ is computed using equation (12), leading to a constant (6×6) matrix.

5. SINGULARITIES IN THE JACOBIAN

Previous work was made by Michel and Rives (1993), related on the singularities of the jacobian from three points, for a 6 dof robot manipulator. The conclusion, for that case, was made in the euclidean space. In this paper is addressed the two features case, for a 2 dof robot manipulator, in the joint space.

As said from the control law, eq. (17), from section 2, the minimization problem has a solution if the jacobian is non-singular. If the jacobian is singular, the control cannot be performed due to the inverse calculus. It is our purpose to study the singularities of the jacobian, in order to avoid them in a path planning scheme.

The first approach was to simply determine the determinant of the jacobian, defined in equation (18) by symbolic manipulation, in order to obtain the singularities, independent from the knowledge of the target position.

$$|J(x, y, Z, q)| = 0$$  \hspace{1cm} (20)

This approach lead us to the impossibility of finding all the values for $q$ that should be avoided during the servoing, with some exceptions that will be presented in the next sub-sections. We will have to know the target position, $x$, $y$, and $Z$ values, to obtain all the singularities.

If the target position is known a-priori, we can obtain directly the $Z$ value and determine the geometric relations between $x$, $y$ and the joint angles $q$. Since $^0T_e$ and $^0T_r$ are known, we can use the pin-hole camera model, equation (2), to obtain the stated relation.

$$|J(q)| = 0$$  \hspace{1cm} (21)

This analysis is valid if we have a pre-defined position to achieve, and want to avoid the singularities, introduced by the vision control law, during the servoing.

5.1 Eye-to-Hand Setup.

In this configuration, the jacobian is different from eq. (18), because the camera is now fixed, not moving with the end-effector.

$$J(x, y, Z, q) = J(x, y, Z) \cdot W_0 \cdot M \cdot ^0J_e(q)$$

The transformation between the world and the fixed camera frames can be defined in a generic way:

$$^0T_e = \begin{bmatrix} 1 & 0 & 0 & X_e \\ 0 & 1 & 0 & Y_e \\ 0 & 0 & 1 & Z_e \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

After determining the jacobian using the first approach, few information can be drawn.

$$|J(x, y, Z, q)| = l_1 \cdot (Y_e + y \cdot Z) \cdot \cos(q_1) - (X_e + x \cdot Z) \cdot \sin(q_1)$$

(22)

The two first results were expected, due to the pin-hole camera model used, but are only theoretical. The third result give us singularity relations between $q_1$, $X_e$, $Y_e$, and $Z$ variables, but all interdependent as we can see in the next expression, obtained solving eq. (22) in order to $q_1$.

$$q_1 = \tan^{-1} \left( \frac{Y_e + y \cdot Z}{X_e + x \cdot Z} \right)$$

In this particular configuration it is possible to obtain the singularities of the jacobian, expressed only in the joint space, fig. 6. This is because the rotation components of the jacobians have no effect (will be set to zero), since the camera is fixed outside the robot, the end-effector is the target and the robot and image planes are parallel.

$$J(x, y, Z, q) = l_1 \cdot l_2 \cdot \sin(q_2)$$

$$|J(q)| = 0 \Rightarrow Z = 0 \vee Z = \infty \vee q_1 = 0 \vee q_2 = \pm \pi$$

Fig. 6: Plot of $|J(q)| = 0$ in the robot workspace, eye-to-hand camera configuration.

Joint space path ($s1$-$s2$).
5.2 Eye-in-Hand Setup.

Camera looking in front

After determining the jacobian using the first approach, few information can be drawn.

\[
\mathcal{J}(x,y,z,q) = \frac{y \cdot l_z \cdot [l_z \cdot \sin(q_z) + \cos(q_z) \cdot x \cdot Z + Z \cdot \sin(q_z)]}{Z^2}
\]

The jacobian has singularities if the following condition is true:

\[
Z = 0 \lor Z = \infty \lor y = 0 \lor \\
l_z \cdot \sin(q_z) + \cos(q_z) \cdot x \cdot Z + Z \cdot \sin(q_z) = 0
\]

This first two results were expected, due to the pin-hole camera model used. The third result means that the image features that belong to the line \( y=0 \), the horizontal line that intersect the optical axis of the camera, puts the second row of the image jacobian to zero, leading the jacobian to singularity. Solving the fourth expression in order to \( q_2 \), we obtain:

\[
q_2 = -\tan^{-1} \left( \frac{x \cdot Z}{l_z + Z} \right)
\]

Knowing the target position, see section 4.2, is possible to obtain the singularities of the jacobian, expressed only in the joint space. We have used generic coordinates for the target position:

\[
\begin{bmatrix}
X_o \\
Y_o \\
Z_o \\
1
\end{bmatrix}
\]

Camera looking down

After determining the jacobian using the first approach, few information can be drawn.

\[
\mathcal{J}(x,y,z,q) = \frac{-l_z \cdot [l_z \cdot \sin(q_z) + \cos(q_z) \cdot x \cdot Z + y \cdot Z \cdot \sin(q_z)]}{Z^2}
\]

The jacobian has singularities if the following condition is true:

\[
Z = 0 \lor Z = \infty \lor \\
l_z \cdot \sin(q_z) + \cos(q_z) \cdot x \cdot Z + y \cdot Z \cdot \sin(q_z) = 0
\]

(24)

The first two results were expected, due to the pin-hole camera model used. Solving the third expression in order to \( q_2 \), we obtain:

\[
q_2 = -\tan^{-1} \left( \frac{x \cdot Z}{l_z + y \cdot Z} \right)
\]

6. SIMULATION RESULTS FOR 2D VISUAL SERVOING

A Matlab™ 6.0 model was developed and validated in (Gonçalves, 2001). In this section are presented the results obtained, when performing 2D visual servoing, with two image features and different camera configurations, for the regulator control.

The following figures show the simulations results for the target positions defined in section 4. Since the singularities were pre-determined, we can define the initial and target positions far from them and ensure that are not crossed.

Fig. 6, show the joint space path \((s1-s2)\) corresponding to figures 7 and 8. Here the singularity is crossed but the servoing still converge. When the
robot is near the singularity the jacobian becomes ill conditioned and the robot diverges from the desired position, about 0.5 sec of the servoing, and then it converges again, as seen in figs. 7 and 8.

7. CONCLUSIONS AND FUTURE WORK

In this paper we studied three camera configurations to perform 2D Visual Servoing. The camera configurations used were: eye-to-hand; eye-in-hand with the camera looking respectively in front and down.

The two contributions were the comparison of three camera configurations for 2D Visual Servoing and finding the singularities of the jacobian, relating the image features velocity to the joint velocity.

The jacobian singularities were determined in section 5, by two different approaches. The first one is independent from the knowledge of the target position, and we have obtained some results that were expected due to the pin-hole camera model. In both eye-in-hand configurations a relation between \( q \) and \( x, y, Z \) coordinates could be found. In eye-to-hand configuration, relations between \( x, y, Z \), \( q \) can be obtained, but all interdependent. Another result was found in the eye-in-hand configuration, camera “looking in front”, when the image features are located in the image horizontal line \( y=0 \). This result physically means that when the image features and the optical axis of the camera belong to the robot plane, the robot cannot be controlled. This is because we have 2 dof to control and only one image feature, not null, to perform control. This singularity can be avoided if we use as image features, the \( x \) coordinates of two different points of the target.

In the second approach we know the target position. This lead us to a jacobian only dependent on the joint coordinates, two variables. With the expressions presented in section 5, for the three camera configurations, it is now possible to determine the jacobian singularities in the joint space. This information will be very useful when performing path planning schemes. In the eye-in-hand cases, this approach shows new conditions for singularities depending on the joint coordinate \( q \). In the eye-to-hand configuration, the singularities are the same as in the classical robot jacobian, \( q_z = 0; q_2 = \pm \pi \).

A very interesting result also obtained is that the robot jacobian singularities \( (q_z = 0; q_2 = \pm \pi) \) may not appear in the total jacobian singularities. This result is in most cases valid and can be explained because of the three transformations needed to perform Visual Servoing, the image jacobian, the matrix “\( W \)”, and the robot jacobian. When the target is the end-effector, in the eye-to-hand configuration, and the optical axis is perpendicular to the robot plane, the jacobian singularities are the same has the robot jacobian singularities. In this case we have no perspective transformation, because the image plane is perpendicular to the robot plane.

From the simulation results presented we can observe the desired exponential decayment of the error vector, during the servoing. For the three camera trajectories simulated the results obtained are very satisfactory. When the robot finds a jacobian singularity, see fig. 6, the servoing can cross it as explained in section 6.

To completely tackle this problem we need to study a path planning scheme capable to avoid (when a cross is not mandatory) the jacobian singularities for a 2 dof planar robot manipulator, and then apply the Visual Servoing algorithms to our robot.

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