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Visual Based Control Scheme for a Robotic Manipulator with Duality of Task-Space Information and Friction Compensation

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Abstract

This paper presents a new control technique for a robot manipulator with dual task-space information and friction compensation. The control scheme allows the end effector to transit smoothly from Cartesian-space feedback to vision-space feedback when the target is inside the vicinity of the camera. An adaptive term is integrated into the proposed controller to compensate the uncertainty associated with parameters in the friction model, including the Striebeck effect. A Lyapunov-like function is presented for stability analysis of the proposed control law. Numerical simulations are presented to demonstrate the performance of the proposed control law for robot manipulator.

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Keywords: adaptive control; region control; visual control; robot manipulator

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{r} \in \mathbb{R}^p$</td>
<td>velocity vector of the end-effector</td>
</tr>
<tr>
<td>$\dot{q} \in \mathbb{R}^n$</td>
<td>joint-space velocity vector</td>
</tr>
<tr>
<td>$J_m(q) \in \mathbb{R}^{p \times n}$</td>
<td>Jacobian matrix from joint space to task space</td>
</tr>
<tr>
<td>$x = [x_1, x_2, \ldots, x_m]^T \in \mathbb{R}^m$</td>
<td>vector of image features</td>
</tr>
<tr>
<td>$J_i(r) \in \mathbb{R}^{m \times p}$</td>
<td>image Jacobian matrix</td>
</tr>
</tbody>
</table>

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1. Introduction

In most industrial robotic arm applications, a desired position for the end-effector is usually specified in the task space such as the Cartesian space or visual space. The basic idea of task-space control is to derive a control scheme using the Cartesian error or visual error directly so that the requirement of solving the inverse kinematics can be omitted. Moreover, the task-space controllers are required to compensate the parameter uncertainties. A Cartesian-space regulator was initially proposed by Takegaki and Arimoto [1]. It was shown using Lyapunov’s method that the PD control plus gravity compensation is effective for set-point control despite the nonlinearity and uncertainty of the robot dynamics. With regards to uncertainty associated with parameters in the friction model, numerous friction compensation schemes have been proposed by researchers. Due to system instability at high gain and unsatisfactory steady-state error results associated with the utilization of conventional PD control scheme [2], adaptive control schemes have been presented that were formulated based on on-line estimation of parameters of dynamic friction models. An adaptive friction compensation control law with a partially known dynamic friction model has been proposed in [3]. In [4], an adaptive control law is reported to compensate the static, Coulomb and viscous friction elements as well as inertia and Striebeck effects, while in [5] a controller is proposed to compensate the parameter uncertainties with the LuGre dynamic friction model of robot manipulators.

Within the visual servoing concept, the positions of the end-effector are represented by the image coordinates. Given the exact image Jacobian matrix of the mapping from Cartesian space to image space, then the task space controllers can be directly extended to image-space controllers. Nevertheless, the image Jacobian matrix poses uncertainty if there exists modeling and calibration errors. Despite the fact that much progress has been presented in the literature of visual servoing [6, 7, 8], there are only a few results obtained for the stability analysis in presence of the uncertain camera parameters as reported in [9]. Nevertheless, the effects of nonlinearity and uncertainties of the robot kinematics and dynamics are not taken into consideration. Note that the concept of duality of task-space information is also presented in [9] and it can be illustrated as in Fig. 1. The approximate Jacobian controller can be used in visual servoing with uncertain camera parameters, taking the nonlinearity and uncertainty of robot kinematics and dynamics into consideration [10]. On the other hand, image based controller as proposed in [11] can be used for depth uncertainty.
Fig. 1. An illustration of a visual based control scheme for a robot manipulator with dual task-space information

In this paper, an adaptive vision based control law with duality of information and friction compensation is presented for a robotic manipulator. The controller is designed to allow the convergence of the end-effector to the desired position in image space regardless of the existence of uncertainty associated with the parameters in the friction model, including the Strubeck parameter. The rest of the paper is organized as follows. Section II describes the kinematic and dynamic properties of a robot manipulator. In Section III, the adaptive vision based control scheme with duality of information and friction compensation is briefly explained. The stability analysis using a Lyapunov-like function is also given in this section. In Section IV, numerical simulation results are provided to demonstrate the performance of the proposed control. Finally, summary and conclusions are presented in Section V.

2. Kinematic and Dynamic Model of a Manipulator

Consider a robotic system with a camera fixed in the work space. The velocity of the end-effector \( \dot{r} \in \mathbb{R}^p \) is related to joint-space velocity \( \dot{q} \) as [12]

\[
\dot{r} = J_m(q) \dot{q}
\]

(1)

where \( q = [q_1, \ldots, q_n] \in \mathbb{R}^n \) is a vector of joint angles of the manipulator and \( J_m(q) \in \mathbb{R}^{p \times n} \) is the Jacobian matrix from joint space to task space.

For a visual servoing system, cameras are used to observe the position of the end-effector in image space. A standard pinhole camera model can be utilized for the mapping from Cartesian space to image space, which has been proven adequate for most visual servoing tasks. Let \( x = [x_1, x_2, \ldots, x_m]^T \in \mathbb{R}^m \) denotes a vector of image features, where \( m \) is the number of image features. The relationship between rate of change of the image features and the velocity of end-effector is represented by an image Jacobian matrix \( J_l(r) \in \mathbb{R}^{m \times p} \) as [7]:

\[
\dot{x} = J_l(r) \dot{r}
\]

(2)

From equation (1) and (2),

\[
\dot{x} = J_l(r) J_m(q) \dot{q} = J(q) \dot{q}
\]

(3)

where \( J(q) \in \mathbb{R}^{m \times n} \) is the Jacobian matrix mapping from joint space to image space. The equation of motion of the robot manipulator with \( n \) degrees of freedom is given in joint space as [12,13];

\[
M(q) \ddot{q} + \left( \frac{1}{2} \dot{M}(q) + S(q, \dot{q}) \right) \dot{q} + \left( F_s \exp(-F_s q^2) \right) \text{sat}(\dot{q}) = \tau
\]

(4)

where \( M(q) \in \mathbb{R}^{n \times n} \) is an inertia matrix that is symmetric and positive definite; \( F_s \) denotes the static friction-related constant; \( F_r \) represents a positive constant corresponding to the Strubeck effect; and \( \tau \in \mathbb{R}^n \) denotes the control inputs and

\[
S(q, \dot{q}) \dot{q} = \frac{1}{2} M(q) \ddot{q} - \frac{1}{2} \left( \frac{\partial}{\partial q} q^T M(q) \dot{q} \right)
\]

Equation (4) is a simplified version of the parameter model presented in [14] and the discontinuous function \( \text{sat}(\cdot) \) is a first-order, differentiable saturation function as shown below:
\[ \text{sat}(\cdot) = \begin{cases} 1 & \text{for } \dot{q} > 0 \\ 0 & \text{for } \dot{q} = 0 \\ -1 & \text{for } \dot{q} < 0 \end{cases} \] (5)

3. Adaptive Vision Based Control Law with Duality of Information and Friction Compensation

In this section, an adaptive controller that is combined with the vision and Cartesian-space region control techniques is proposed to ensure an end-effector tracks the desired trajectory in image space while compensating the uncertainty associated with the parameters in the friction model. The control law is formulated as follows:

First the desired trajectory of the end effector in image space is introduced as \( x_{d}(t) = [x_{1d}, x_{2d}, ..., x_{md}]^T \in \mathfrak{R}^m \). Then a region for the desired end effector position can be defined as the scalar function

\[ f_{x}(\Delta x) = (x_{1} - x_{1d})^2 + (x_{2} - x_{2d})^2 + \cdots + (x_{m} - x_{md})^2 \leq r_x \] (6)

where \( \Delta x = x - x_d \) and \( r_x \) is a positive constant.

From (6), the potential energy function can be represented as follows [9]

\[ P_{x}(x) = \frac{k_{px}}{2} \left( r_x^2 - \left[ \min \left( 0, f_{x}(\Delta x) \right) \right]^2 \right) \] (7)

where \( k_{px} \) is a positive scalar. Differentiating (7) with respect to \( x \) gives

\[ \left( \frac{\partial P_{x}(x)}{\partial x} \right)^T = -k_{px} \min \left( 0, f_{x}(\Delta x) \right) \left( \frac{\partial f_{x}(\Delta x)}{\partial x} \right)^T \triangleq \begin{cases} 0, & f_{x}(\Delta x) \geq 0 \\ -k_{px} f_{x}(\Delta x) \left( \frac{\partial f_{x}(\Delta x)}{\partial x} \right)^T, & f_{x}(\Delta x) < 0 \end{cases} \] (8)

Equation (8) can be denoted as the image error \( \hat{e}_{x} \) in the following form

\[ \hat{e}_{x} = -\min \left( 0, f_{x}(\Delta x) \right) \left( \frac{\partial f_{x}(\Delta x)}{\partial x} \right)^T \] (9)

Secondly, introduce a position control term in Cartesian space so that the end effector can be positioned towards \( f_{x}(\Delta x) < 0 \). It leads to the elimination of the need of vision control where the end effector is far away from the desired position. A desired region in Cartesian space in scalar function \( \Re \) can be formulated as

\[ f_{r}(r) = (r_{1} - r_{1c})^2 + (r_{2} - r_{2c})^2 + (r_{3} - r_{3c})^2 \leq \kappa^2 \] (10)

where \( \kappa \) is a positive constant; \( [r_{1}, r_{2}, r_{3}]^T \) is the actual position of the end effector and \( [r_{1c}, r_{2c}, r_{3c}]^T \) is the center position of the workspace. The corresponding potential energy function for the desired region described in (10) can be specified as

\[ P_{r}(r) = \frac{k_{pr}}{2} \left[ \max \left( 0, f_{r}(r) \right) \right]^2 \triangleq \begin{cases} 0, & f_{r}(r) \leq 0 \\ \frac{k_{pr}}{2} f_{r}^2(r), & f_{r}(r) > 0 \end{cases} \] (11)

where \( k_{pr} \) is a positive scalar. Differentiating (11) with respect to \( r \) gives

\[ \left( \frac{\partial P_{r}(r)}{\partial r} \right)^T = k_{pr} \max \left( 0, f_{r}(r) \right) \left( \frac{\partial f_{r}(r)}{\partial r} \right)^T \triangleq \begin{cases} 0, & f_{r}(r) \leq 0 \\ k_{pr} f_{r}(r) \left( \frac{\partial f_{r}(r)}{\partial r} \right)^T, & f_{r}(r) > 0 \end{cases} \] (12)

Now, let (12) be represented as the Cartesian error \( \hat{e}_{r} \)

\[ \hat{e}_{r} = \max \left( 0, f_{r}(r) \right) \left( \frac{\partial f_{r}(r)}{\partial r} \right)^T \] (13)

Remark: To ensure the vector \( \frac{\partial f_{r}(r)}{\partial r} \) is not equal to zero or vanishes when outside the desired region, the function \( f_{r}(r) \) must be properly chosen.
Subsequently, an adaptive region vision based controller for a robot manipulator can be proposed as follows
\[
\tau = -f_m(q)k_{pr}\dot{q} + f_m(q)k_{px}\dot{q} - \dot{K}_uq + \dot{F}_s\text{sat}(\dot{q})\exp(-\dot{F}_r\dot{q}^2)
\]  
(14)
where \(k_{px}\) and \(k_{pr}\) are previously defined in (7) and (11), respectively. \(K_u\) is a positive gain matrix and \(J^T\) is the Jacobian transpose matrix. The parameters \(F_s\) and \(F_r\) in the last term of (14) represent the estimates of \(F_s\) and \(F_r\), respectively, which are formulated according to the following updated laws
\[
\dot{F}_s = -\kappa_0\dot{q}\text{sat}(\dot{q})\exp(-\dot{F}_s\dot{q}^2)
\]  
(15)
and
\[
\dot{F}_r = \kappa_1\dot{q}^3\text{sat}(\dot{q})\exp(-\dot{F}_r\dot{q}^2)
\]  
(16)
where \(\kappa_0\) and \(\kappa_1\) are positive adaptation gains. Substituting (14) into (4) the closed-loop equation is obtained as
\[
\begin{align*}
M(q)\ddot{q} + \left(\frac{1}{2}M(q) + S(q, \dot{q})\right)\dot{q} + J_m^T(q)k_{pr}\dot{q} - J_m^T(q)k_{px}\dot{r}_x + \dot{K}_uq &+ F_s\text{sat}(\dot{q})\exp(-F_s\dot{q}^2) - \exp(-F_s\dot{q}^2) + F_s\text{sat}(\dot{q})\exp(-F_r\dot{q}^2) = 0
\end{align*}
\]  
(17)
Next, the following Lyapunov function is considered
\[
V = \frac{1}{2}\dot{q}^T M(q)q + P_x(x) + P_r(r) + \frac{1}{2\kappa_0}\dot{F}_s^2 + \frac{1}{2\kappa_1}\dot{F}_r^2
\]  
(18)
Differentiation of \(V\) with respect to time gives
\[
\dot{V} = \dot{q}^T Mq + \frac{1}{2}\dot{q}^T M\dot{q} - k_{px} \min(0, f_s(\Delta x)) \dot{q}^T \left(\frac{\partial f_s(\Delta x)}{\partial x}\right)^T + k_{pr} \max(0, f_r(r)) \dot{r}^T \left(\frac{\partial f_r(\Delta r)}{\partial r}\right)^T + \frac{\dot{F}_s}{\kappa_0}\dot{F}_s + \frac{\dot{F}_r}{\kappa_1}\dot{F}_r
\]  
(19)
Substituting (15), (16) and the closed-loop equation (17) into (19) and cancelling common terms, yields
\[
\dot{V} = -\dot{q}^T K_uq - \dot{q}^T F_s\text{sat}(\dot{q})\exp(-F_s\dot{q}^2) - \exp(-F_r\dot{q}^2) - F_s\dot{F}_s\text{sat}(\dot{q})\exp(-F_r\dot{q}^2)
\]  
(20)
where the following equation was considered
\[
\dot{q}^T J_m^T(q)k_{pr}\dot{r}_x - \dot{q}^T J_m^T(q)k_{px}\dot{r}_x
\]  
\[= -k_{px} \min(0, f_s(\Delta x)) \dot{q}^T \left(\frac{\partial f_s(\Delta x)}{\partial x}\right)^T + k_{pr} \max(0, f_r(r)) \dot{r}^T \left(\frac{\partial f_r(\Delta r)}{\partial r}\right)^T
\]  
(21)
Equation (20) can be rewritten as follows
\[
\dot{V} = -\dot{q}^T K_uq - \dot{q}^T F_s\text{sat}(\dot{q})\exp(-\dot{F}_s\dot{q}^2) \cdot \exp(-\dot{F}_r\dot{q}^2) - 1 + \dot{F}_r\dot{q}^2 \leq 0
\]  
(22)
That is,
\[
\dot{V} = -\dot{q}^T K_uq - \dot{q}^T F_s\text{sat}(\dot{q})\exp(-\dot{F}_r\dot{q}^2) \cdot \exp(\zeta - 1) - \zeta \leq 0
\]  
(23)
where \(\zeta = 1 - \dot{F}_r\dot{q}^2\). Since \(\text{sat}(\dot{q})\dot{q} \geq 0\) and \(\exp(\zeta - 1) \geq \zeta\), \(\dot{V}\) can be upper bounded as follows
\[
\dot{V} \leq -\dot{q}^T K_uq
\]  
(24)
Consider a compact set in the state space defined by
\[
\Omega = \{(q, \dot{q}, \dot{F}_s, \dot{F}_r)\}
\]  
(25)
where the integration of potential energy functions \(P_x(x)\) and \(P_r(r)\) has an isolated minimum at the desired position.

Next, the theorem can be stated as:
**Theorem 1:** Given a non-multivalued, discontinuous function of (5) and closed-loop function (17), the proposed control law described by (14) and its updated laws (15) and (16) guarantees the convergence of $\dot{x}$ to the desired position $x_d$ on image space in the sense that $\dot{q}, \dot{e}_r, \dot{e}_i$ are all driven to zero as $t \to \infty$.

**Proof:** Since the closed-loop equation is autonomous, LaSalle's invariance principle can be used to show asymptotic stability. Note that $\dot{V}$ in (18) is positive definite and $\ddot{V}$ is negative semidefinite as described in (24). According to the invariance principle; $\dot{V} = 0$ implies that $\dot{q} = 0$ and the composite vector $\{\dot{e}_r, \dot{e}_i\} = 0 \forall \ q \in \mathbb{R}^n$ taking into account of an isolated minimum at the desired position as defined in (25). Hence, $\dot{q} \to 0$ and $\dot{e}_r, \dot{e}_i \to 0$ as $t \to \infty$ which finally leads to the convergence of $x$ to $x_d$ as $t$ approaches infinity. Note that the invariant set theorem [15], [16] is used to prove the convergence of $x$ to a desired position on the image space. A general theorem on convergence to an invariant set is also presented in [17] for a class of nonlinear systems. However, the systems must be Lipschitz continuous, and hence, cannot be applied to robot systems directly. Like invariant set theorems, the result is useful for general stability analysis, no controller design is presented and the existence of a Lyapunov function is assumed.

4. Simulation Study

In this section, simulation studies are carried out to assess the effectiveness of the proposed vision-based control law for a 2 Degrees-Of-Freedom (DOF) robot manipulator. The main objective is to drive the end-effector into the circular region in image space in spite of it being initialized outside the vision region. The masses and lengths of the manipulator links are set to $m_i = 3.38$ kg and $L_i = 0.33$ m where $i = 1$ and 2. The links are cylindrical and the radii of each link is 0.05 m. The numerical values of the static friction and Stribeck effect related-parameters are set to $F_s = 4.90$ Nm and $F_r = 0.1890$ sec$^2$/rad$^2$, respectively.

A desired position in image space is specified as $x = [100, 50]^T$ pixels and a vision space region was defined as a circle with a radius of 10 pixels, around the desired position. The vision feedback was only used when the end-effector enters this vision region. To move the end effector toward the vision region without vision feedback, a circular region in Cartesian space was defined with the centroid of $r = [0.2, 0.2]^T$ m and a radius of 0.05 m. A Cartesian-space controller is used when the end-effector is located outside the vision region. The best performance of the proposed vision based control can be achieved with the following gains:

$$k_{pr} = 350; k_{px} = 750; k_v = 0.1; \kappa_1 = 0.08$$

$$K_v = \text{diag}([20 \ 20]);$$

![Fig. 2. The manipulator configuration and trajectory for end-effector. The ‘dash-dot line’ marks a desired region for vision.](image-url)
Fig. 3. Position error for the end-effector in image space

Fig. 4. Friction related-parameter estimation

The trajectory of the robot manipulator in configuration space is shown in Fig. 2. The blue lines indicate the initial pose of the two-link manipulator while the red lines are its final pose. The intermediate poses and end-effector straight line trajectory are denoted by yellow and black lines, respectively. Fig. 3 shows the position when the end-effector enters the vision region. The estimation for friction related-parameters, as shown in Fig. 4, converge to constant values after a brief transient phase.

5. Conclusion

A vision based control law with duality of information and friction compensation for a robotic manipulator has been presented in this paper. The controller was designed to allow the convergence of the end-effector to the desired position in image space regardless of the existence of uncertainty associated with the parameters in the friction model, including the Strubeck parameter. The stability is guaranteed using the Lyapunov type approach. Simulation
case studies of a 2-DOF robotic arm have been carried out to demonstrate the validity of the proposed control laws. Future research work focuses on the extension of this proposed framework to handle the bounded external disturbances.

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