Robust Control of Robot Manipulators using Vision Systems

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ABSTRACT

In this paper, we propose a robust controller for trajectory control of n-link robot manipulators using feature based on visual feedback. In order to reduce tracking error of the robot manipulator due to parametric uncertainties, integral action is included in the dynamic control part of the inner control loop. The desired trajectory for tracking is generated from feature extraction by the camera mounted on the end effector. The stability of the robust state feedback control system is shown by the Lyapunov method. Simulation and experimental results on a 5-link robot manipulator with two degree of freedom show that the proposed method has good tracking performance

Key words : visual feedback, robot , robust control, state feedback control, integral control

Ⅰ. Introduction

Visual information is an attractive solution for the position and motion control of robot manipulators working in unstructured environment. A camera mounted on the end effector of the robot manipulator supplies visual information of the object. The control objective of this approach is to move the manipulator in such a way that the projection of feature on either a moving or a static object in the camera frame be always at a desired location in the image captured by the camera [1]. This control problem has attracted the attention of researchers in recent years. In most previous works, robot dynamics do not interact with visual feedback loop. Although this assumption is valid for slow robot motion, it dose not hold for high speed tasks. However robot dynamics are not exactly known because of parametric uncertainties such as an unknown payload or unmodeled joint friction. Eventhough visual feedback is used in robot control system, parametric uncertainties deteriorate the performance of the inner dynamic control loop.

Robust control schemes for robot manipulators [2] are required to achieve good tracking performance in the presence of parametric uncertainties. The robust saturation control techniques are typically applied to guarantee uniform ultimate boundedness of the tracking errors [3]. Most of these schemes require known uncertainty bounds, which is difficult to estimate precisely. Hence, the estimated uncertainty bounds may be very conservative. These conserv-ative bounds lead to excessive large control magnitudes. However, robust control schemes require high feedback gains in order to maintain small tracking errors. In practice, high feedback gains are limited because of hardware issues such as digital implementation, neglected high frequency modes, and actuator saturation. Limitation of high feedback gains induces large tracking errors [4], [5]. To overcome this problem, integral control is introduced.

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Integral control [6] reduces tracking error.

In this paper we proposed a robust feedback controller using visual feedback for trajectory control of n-link robot manipulators with bounded parametric uncertainties. The feature extraction by the camera mounted on the end effector makes the desired position, velocity and acceleration vectors for tracking. The robust controller with integral action reduces tracking error due to the limitation of high feedback gains. The proposed method is implemented on a two degree of freedom 5-link FARA robot.

Ⅱ. Robot Dynamic Model and Control Problem

In the absence of friction, the dynamic equation of an n-link rigid robot can be expressed as [7].

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)=\tau \tag{1}$$

where $q\in R^n$ is the vector of joint displacements, $\tau\in R^n$ is the vector of the torques applied to the joints, $M(q)\in R^{n\times n}$ is the symmetric positive definite inertia matrix, $C(q,\dot{q})\dot{q}$ is the $n\times 1$ vector of centripetal and Coriolis forces and $G(q)$ is the vector of the gravitational force.

By a linear parameterization property of the rigid robot, the equation (1) can be expressed

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)=Y(q,\dot{q},\ddot{q})\Theta \tag{2}$$

where $Y(q,\dot{q},\ddot{q})$ is called the regression matrix and Θ is the $p\times 1$ vector of physical parameters of the robot manipulator.

Let us consider a camera mounted at the robot end effector. When an object point with coordinates $[X \quad Y \quad Z]^T$ in the camera frame projects onto a point on the image plane, the image feature point of the object in the image plane is given by

$$\xi=\begin{bmatrix} x \\ y \end{bmatrix}=\frac{f}{Z}\begin{bmatrix} \frac{X}{\alpha} \\ \frac{Y}{\beta} \end{bmatrix} \tag{3}$$

where f is a focal length of the camera and α, β are the scaling factors in pixels per meter due to the camera sampling. The time derivative of the position vector ξ yields

$$\dot{\xi}=\frac{f}{Z}\begin{bmatrix} \frac{1}{\alpha} & 0 & -\frac{X}{\alpha Z} \\ 0 & \frac{1}{\beta} & -\frac{Y}{\beta Z} \end{bmatrix}\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} \tag{4}$$

The time derivative of the object point can be expressed as follows

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix}=\begin{bmatrix} -1 & 0 & 0 & 0 & -Z & Y \\ 0 & -1 & 0 & Z & 0 & -X \\ 0 & 0 & -1 & -Y & X & 0 \end{bmatrix}\begin{bmatrix} R_c^T(q) & 0 \\ 0 & R_c^T(q) \end{bmatrix}\begin{bmatrix} v_c \\ \omega_c \end{bmatrix} \tag{5}$$

where R_c^T is the rotational matrix of the camera frame with respect to the robot coordinate frame and v_c and $\omega_c$stand for the camera linear and angular velocities with respect to the robot frame, respectively.

Substituting (5) into (4), the motion of the image feature point is obtained

$$\dot{\xi}=J_{img}(\xi,Z)\begin{bmatrix} R_c^T(q) & 0 \\ 0 & R_c^T(q) \end{bmatrix}\begin{bmatrix} v_c \\ \omega_c \end{bmatrix} \tag{6}$$

where

$$J_{img}(\xi,Z)=\begin{bmatrix} -\frac{f}{\alpha Z} & 0 & \frac{x}{Z} & \frac{\beta xy}{f} & -\frac{f^2+\alpha^2x^2}{\alpha f} & \frac{\beta y}{\alpha} \\ 0 & -\frac{f}{\beta Z} & \frac{y}{Z} & \frac{f^2+\beta^2y^2}{\beta f} & -\frac{\alpha xy}{f} & -\frac{\alpha x}{\beta} \end{bmatrix} \tag{7}$$

Since the joint velocities $\dot{q}$ and the corresponding end-effector translational velocity v_c and angular velocity ω_c are related via the geometric Jacobian $J_g(q)$: [8].

$$\begin{bmatrix} v_c \\ \omega_c \end{bmatrix} = J_g(q)\,\dot{q} \tag{8}$$

the time derivative of the image feature vector can be expressed as

$$\dot{\xi} = J(q, \xi, Z)\,\dot{q} \tag{9}$$

where

$$J(q, \xi, Z) = J_{img}(\xi, Z)\begin{bmatrix} R_c^T & 0 \\ 0 & R_c^T \end{bmatrix} J_g(q) \tag{10}$$

Let us denote with ξ_d the desired image feature vector and define the image feature error

$$\tilde{\xi} = \xi_d - \xi \tag{11}$$

Assuming ξ_d be a constant vector, the time derivative of (11) is given by

$$\dot{\tilde{\xi}} = -J(q, \xi, Z)\,\dot{q} \tag{12}$$

We take

$$\dot{q} = J^+(q, \xi, Z) K_v \tilde{\xi} \tag{13}$$

where K_v is positive definite gain matrix to be designed and $J^+(q, \xi, Z)$ is the pseudo-inverse matrix of the image Jacobian such that

$$J^+(q, \xi, Z) = [J^T(q, \xi, Z) J(q, \xi, Z)]^T J^T(q, \xi, Z) \tag{14}$$

Substituting (13) into (12), the error dynamic equation is given by

$$\dot{\tilde{\xi}} = -K_v \tilde{\xi} \tag{15}$$

The gain matrix K_v can be chosen such that the error vector $\tilde{\xi}$ converges to zero as $t \to \infty$.

For state feedback control, we use (13) as the desired joint velocity vector $\dot{q}_d$. Then the desired position vector q_d and the acceleration vector $\ddot{q}_d$ are generated by integrating and differentiating $\dot{q}_d$, respectively.

Let us define the set of the desired position, velocity and acceleration vector

$$Q_d = [q_d^T \quad \dot{q}_d^{\,T} \quad \ddot{q}_d^{\,T}]^T$$

It is assume that Q_d belongs to the compact set $Q_D \subset R^{3n}$ and the gravitational forces are bounded.

The control objective is to design a robust state feedback controller with integral action in order to reduce tracking error in the presence of bounded parameter uncertainties due to load variation.

Ⅲ. Robust State Feedback Control

Defining the tracking error as $e = q - q_d$, the error dynamic equation for robot manipulators of (1) is described by

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -\ddot{q}_d - M^{-1}(x_1, q_d)[C(x, q_d, \dot{q}_d) \\ &\quad (x_2 + \dot{q}_d) + G(x_1, q_d) + \tau] \end{aligned} \tag{16}$$

where $x_1 = e$, $x_2 = \dot{e}$, and $x = [x_1^T x_2^T]^T$.

We augment the state equation (16) with an integrator driven by the tracking error of each joint position:

$$\sigma_i = \kappa \int_0^t e_i(\tau)d\tau \quad i = 1, 2, \cdots, n \tag{17}$$

where $\kappa > 0$ is the design parameter to be determined. Hence, the augmented state equation is given by

$$\dot{\zeta} = A\zeta + BM^{-1}(x_1, q_d)[-Y(x, Q_d)\Theta + \tau] \tag{18}$$

where $\zeta = [\sigma^T x_1^T x_2^T]^T$,

$$A = \begin{bmatrix} 0 & \kappa I & 0 \\ 0 & 0 & I \\ 0 & 0 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 0 \\ I \end{bmatrix} \tag{19}$$

and

$$Y(x, Q_d)\Theta = (x_1, q_d)\ddot{q}_d + C(x, q_d, \dot{q}_d)(x_2 + \dot{q}_d) + G(x, q_d) \tag{20}$$

We assume that the vector θ is constant but unknown and θ_0 is the nominal value of θ. For the nominal vector θ_0, (20) becomes

$$Y(x, Q_d)\Theta_0 = M_0(x_1, q_d)\ddot{q}_d + C_0(x, q_d, \dot{q}_d)(x_2 + \dot{q}_d) + G_0(x_1, q_d) \tag{21}$$

where $M_0(\cdot), C_0(\cdot)$ and $G_0(\cdot)$ are nominal matrices of $M(\cdot), C(\cdot)$ and $G(\cdot)$ respectively. We make the following assumptions on the robot dynamics (1).

Assumption 1: There exist positive constants λ_m and λ_M such that

$$\lambda_m \leq ||M^{-1}(q)|| \leq \lambda_M \tag{22}$$

Assumption 2: There exist positive constants $\alpha_M, \alpha_C, \alpha_G$, and a positive function $\beta_0(\zeta) = \beta_1 + \beta_2||\zeta|| + \beta_3||\zeta||^2$ such that

$$||M_0(q) - M(q)|| \leq \alpha_M \tag{23}$$

$$||C_0(q, \dot{q}) - C(q, \dot{q})|| \leq \alpha_C||\dot{q}|| \tag{24}$$

$$||G_0(q) - G(q)|| \leq \alpha_G \tag{25}$$

$$||Y(x, Q_d)(\Theta_0 - \Theta)|| \leq \beta_0(\zeta) \tag{26}$$

where $\beta_1 \geq \alpha_M||\ddot{q}_d|| + \alpha_C||\dot{q}_d|| + \alpha_G$, $\beta_2 \geq 2\alpha_C||\dot{q}_d||\beta_2 \geqq 2\alpha_C\ |\dot{q}_d|$ and $\beta_3 \geqq \alpha_C$.

We propose a robust state feedback controller

$$\tau = Y(x, Q_d)\Theta_0 + M_0(x_1, q_d)K\zeta + \tau_n \tag{27}$$

where, K is the gain matrix to be defined and $Y(x, Q_d)\theta_0 + M_0(x_1, q_d)K\zeta$ is a nominal control input term and τ_n is a nonlinear control input term to achieve robustness to the bounded parametric uncertainties.

The nonlinear term τ_n is taken as:

$$\tau_n = \begin{cases} -\dfrac{\lambda_M\beta(\zeta)s}{\lambda_m\|s\|} & \text{if } \lambda_M\beta(\zeta)\|s\| \geq \mu \\ -\dfrac{\lambda_M^2\beta^2(\zeta)s}{\mu\lambda_m} & \text{if } \lambda_M\beta(\zeta)\|s\| < \mu \end{cases} \tag{28}$$

where μ is a design parameter to be chosen, $s = B^T P\zeta$, $\beta(\zeta) = \beta_0(\zeta) + \alpha_M\ |K|\ |\zeta|$, and $P = P^T$ is the solution of the Lyapunov equation

$$(A + BK)^T P + P(A + BK) = -I \tag{29}$$

Theorem 1: Suppose that assumption 1 and 2 hold. Given the error dynamic equation of (19) the proposed controller of (27) and (28) ensures link position tracking errors to be bounded in finite time.

Proof: We take the Lyapunov function candidate

$$V = \zeta^T P \zeta \tag{30}$$

For $c > 0$, define

$$\Omega_c = \{\zeta \in R^{3n} V(\zeta) \leq c\} \tag{31}$$

where Ω_c belongs to the ball B_0 defined by $B_0 = \{\zeta \in R^{3n}: ||\zeta \; r|| \}$ inside Ω_c, we have $||\zeta||^2 \leq \frac{c}{\lambda_m(P)}$

The time derivative of V along the trajectory of (19) leads to

$$\dot{V} \leq -\|\zeta\|^2 + 2\lambda_M \|s\| \beta(\zeta) + 2s^T M^{-1}(x_1, q_d)\tau_n \tag{32}$$

For all $\zeta \in \{\zeta : \{\lambda_M \beta(\zeta)||s|| > \mu \cap \Omega_c\}\}$ we have

$$\dot{V} \leq -||\zeta||^2 \tag{33}$$

while for all $\zeta \in \{\zeta : \{\lambda_M \beta(\zeta)||s|| \leq \mu \cap \Omega_c\}\}$, we have

$$\dot{V} \leq -||\zeta||^2 + 2\mu \tag{34}$$

For $\mu \leqq \frac{c}{2\alpha\lambda_{\max}(P)}$, with $\alpha > 1$, the inequality of (34) becomes

$$\dot{V} \leq -2\mu(\alpha - 1) \tag{35}$$

This implies that the set $\Omega_\mu = \{\lambda_M \beta(\zeta) \; |s| \leqq \mu\}$ is positively invariant set and ξ will approach the set Ω_μ in finite time.

Ⅳ. Simulation and Experiment

In order to demonstrate the efficiency of the proposed robust controller, computer simulations and an experiment are performed on a 2-degree of freedom of 5-link Samsung FARA robot. The dynamic equation of the manipulator is given by

$$\begin{bmatrix} M_{11}(q) & M_{12}(q) \\ M_{21}(q) & M_{22}(q) \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} + \begin{bmatrix} C_{11} & C_{12} \\ C_{12} & C_{22} \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} G_1(q) \\ G_2(q) \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \tag{36}$$

where,

$$M_{11}(q) = m_1 l_{c2}^2 + m_3 l_{c3}^2 + m_4 l_1^2 + I_1 + I_3$$
$$M_{12}(q) = (m_3 l_2 l_{c3} - m_4 l_1 l_{c4})\cos(q_2 - q_1)$$
$$M_{21}(q) = (m_3 l_2 l_{c3} - m_4 l_1 l_{c4})\cos(q_2 - q_1)$$
$$M_{22}(q) = (m_3 l_2 l_{c3} - m_4 l_1 l_{c4})\cos(q_2 - q_1)$$
$$C_{11}(q, \dot{q}) = 0$$
$$C_{12}(q, \dot{q}) = -(m_3 l_2 l_{c3} - m_4 l_1 l_{c4})\sin(q_2 - q_1)\dot{q}_2$$
$$C_{21}(q, \dot{q}) = (m_3 l_2 l_{c3} - m_4 l_1 l_{c4})\sin(q_2 - q_1)\dot{q}_2$$
$$C_{22}(q, \dot{q}) = 0$$
$$G_1 = g(m_1 l_{c1} + m_3 l_{c3} + m_4 l_1)\cos q_1$$
$$G_2 = g(m_2 l_{c2} + m_3 l_2 - m_4 l_{c4})\cos q_2$$

The parameter values are given by

$m_1 = 5.5Kg$, $m_2 = 0.3Kg$,
$m_3 = 0.2Kg$, $m_4 = 4.5Kg$
$l_1 = 0.35m$, $l_2 = 0.140m$
$l_{c1} = 0.175m$, $l_{c2} = 0.707m$,
$l_{c3} = 0.175m$, $l_{c4} = 0.250m$
$I_1 = 0.04Kgm^2$, $I_2 = 0.003Kgm^2$,
$I_3 = 0.001Kgm^2$, $I_4 = 0.06Kgm^2$
$g = 9.8m/s^2$

By denoting with ϕ, χ, and ψ , the ZYZ Euler angles for parameterization of camera orientation, we obtain the direct kinematics equation

$$ {}^{c}p_{o} = \begin{bmatrix} p_y \\ p_y \\ p_y \\ \phi \\ \chi \\ \psi \end{bmatrix} = \begin{bmatrix} l_1 \cos q_1 - l_4 \cos q_2 \\ l_1 \sin q_1 - l_4 \sin q_2 \\ 0 \\ q_2 - \pi \\ 0 \\ 0 \end{bmatrix} \quad (37) $$

where we have used the fact that $\phi = q_2 - \pi$, $\chi = \psi = 0$, because the arm moves in the plane x-y.

The analytical Jacobian is computed by differentiating the direct kinematics equation (37)

$$ J_A(q) = \frac{\partial\, {}^{c}p_0}{\partial q} = \begin{bmatrix} -l_1 \sin q_1 & l_4 \sin q_2 \\ l_1 \cos q_1 & -l_4 \cos q_2 \\ 0 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (38) $$

The transformation matrix $T(q)$ which relates the camera angular velocity to the time derivative of the Euler angles is

$$ w2 = w1 \left(1 - q \cos\left(\frac{\pi x}{P} \right) \right) $$

$$ T(q) = \begin{bmatrix} 0 & -\sin(-\pi + q_2) & 0 \\ 0 & \cos(-\pi + q_2) & 0 \\ 1 & 0 & 1 \end{bmatrix} \quad (39) $$

The rotation matrix of the camera frame with respect to the robot frame is given by

$$ R_c^T = \begin{bmatrix} -\cos q_2 & -\sin q_2 & 0 \\ \sin q_2 & -\cos q_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (40) $$

The focal length of the camera is $f = 0.016m$ and the scaling factors of the X-axis and Y-axis are $\overline{\alpha} = 6.941 \times 10^{-6} m/\pi xel$ and $\overline{\beta} = 9.4251 \times 10^{-6} m/\pi xel$. It is assumed that the initial angles of Joint 1 and Joint 2 are $q_1 = \pi/2(rad)$ and $q_2 = \pi(rad)$. We assume the initial feature point is $\xi^T = [100\ \ 100]^T$ and the desired feature point is $\xi_d^T = [0\ \ 0]^T$. We also assume that a payload of around $5.5Kg$ is added to the mass m_4 and the other parameters are not affected by this added payload. We take design parameters $\mu = 1$ and $\kappa = 1$ outside the set Ω_μ and $\kappa = 10$ inside the set Ω_μ. The control gain matrix is chosen as $K = [-5I\ \ -100I\ \ -50I]$. The control param -eters of the nonlinear terms are set as $\lambda_m = 1.44$ and $\lambda_M = 8.33$ and, $\beta_1 = 291.17$, $\beta_2 = 72.25$ and $\beta_3 = 12.5$.

Computer simulations are performed using MATLAB. Figure 1 and 2 are simulation results by the proposed control scheme. The results by

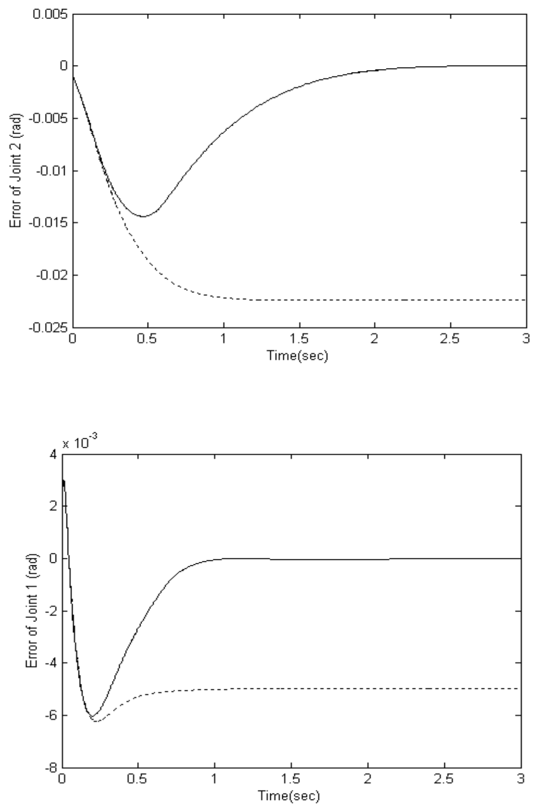

Fig 1. Simulation results: position tracking errors of link 1 and 2 using the proposed control (solid) and robust control without integral action(dashed)

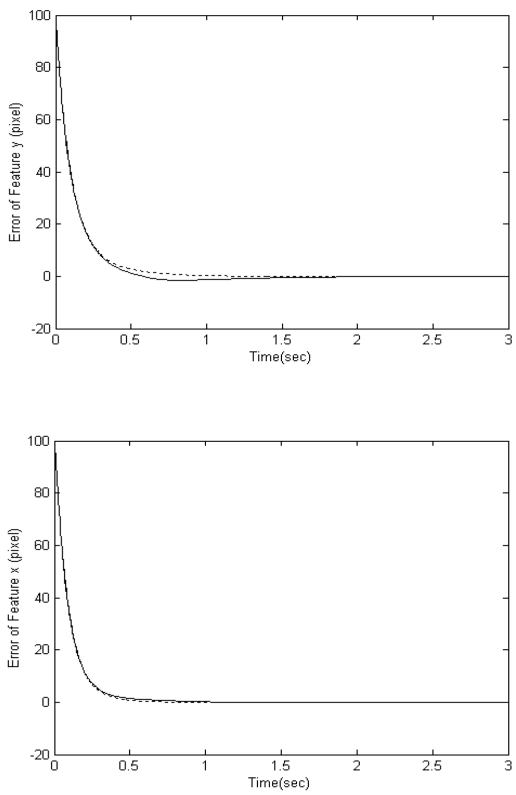

Fig 2. Simulation results: feature tracking errors of link 1 and 2 using the proposed control (solid) and robust control without integral action(dashed)

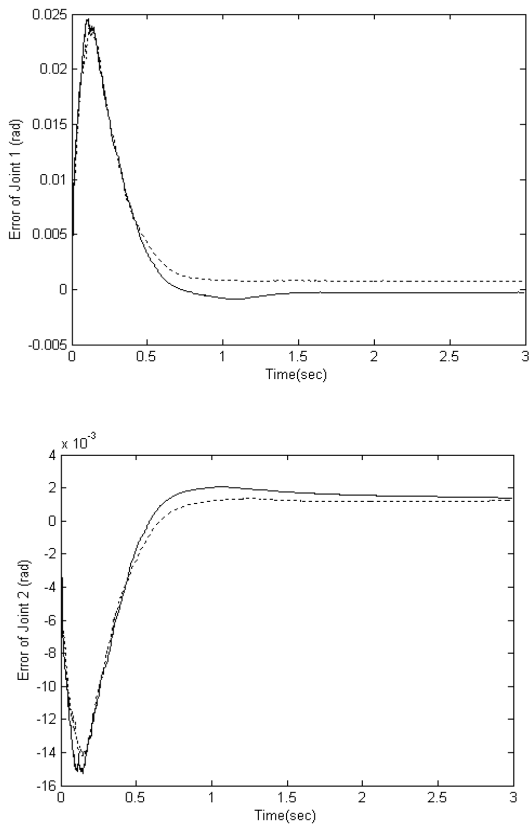

Fig 3. Experimental results: position tracking errors of link 1 and 2 using the proposed control (solid) and robust control without integral action(dashed)

the proposed method are compared to those without integral action. Experimental results on 5-link Samsung FARA robot applying the proposed method are shown in Figure 3 and 4. Since load variation does not make during this experiment, it is not distinguished the advantage of the proposed method in figures. However experimental results show that the proposed method make each link track the desired joint position generated by the camera mounted on the end-effector. Hence the proposed one can be implemented to the industrial robot control.

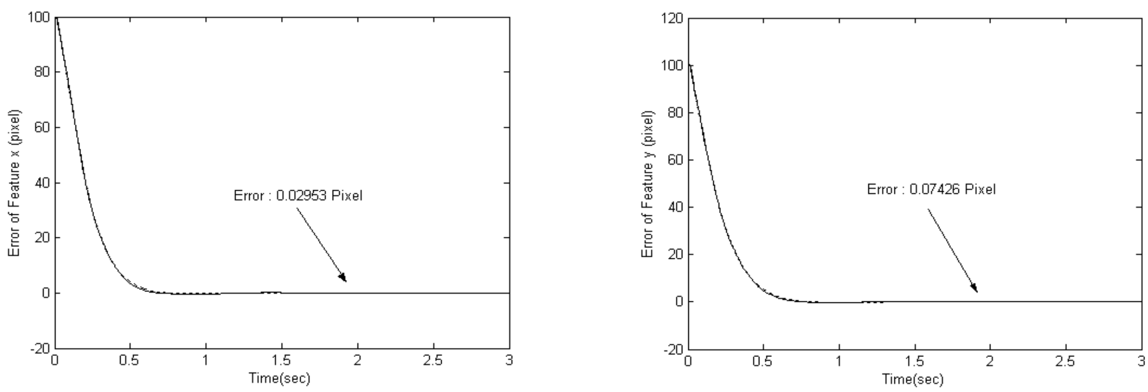

Fig 4. Experimental results: feature tracking errors of link 1 and 2 using the proposed control (solid) and robust control without integral action(dashed)

V. Conclusion

A new robust state feedback controller with visual feedback for robot manipulators is proposed. The feature extraction by the camera mounted on the end effector makes the desired position, velocity and acceleration vectors for tracking. The proposed controller with integral action reduces tracking error due to parametric uncertainties. Integral part is designed to have lower gain during transient and higher gain after tracking error is under predetermined level. This scheme avoids wind-up phenomenon and improves the control performance in steady-state. The stability of the robust state feedback is shown by the Lyapunov method. The proposed method as been implemented on 5-link FARA robot with two degree of freedom. Simulation and experiment results show that good tracking performance is obtained.

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