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Robust Backstepping Control of Robot Manipulator in Task Space with Uncertainties in Kinematics and Dynamics

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Introduction

Industrial robots are commonly controlled in joint space to perform position control [1]. In practice, for tracking a trajectory in task space, an industrial robot follow a desired trajectory in joint space which is already recorded in a learning process called the "teach and play back" technique. Actually, the transformation from task space to joint space is realized perfectly by this technique while a computed transformation such as inverse kinematics may involve model uncertainties. This technique works well if the transformation to be repeatable. Thus, it is not surprising if a joint space control can provide a desired tracking performance in task space without feedbacks from the end-effector position since an industrial robot is constructed in a high quality with a good repeatability, precision and resolution to overcome uncertainties.

In joint space control, feedbacks from joint space are given to control system for tracking a desired trajectory. This control system does not detect the position error of end-effector in work space. Even if a precise tracking of joint positions is achieved, a desired tracking in task space is not provided by the use of imperfect transformation of control space. Thus, due to detecting tracking error of the end-effector, task-space tracking control of a normal-cost robot is superior to joint space control. It means that we can expend less cost to achieve a desired performance by a task-space control of a normal-cost robot in replace of joint-space control an expensive robot. However, obtaining feedbacks from task-space is not as convenient as joint-space. The joint positions are measured suitably by optical encoders while end-effector position may be detected using vision systems [2-3].

There is a challenge in robot control to overcome uncertainties, nonlinearities and couplings from different aspects in the field of robust control as surveyed in [4-7]. The robust control provides stability under uncertainties with a trade off between tracking performance and bounds of uncertainties. This control approach was extensively presented in joint space while controlling a robot in task space is still a control problem. Recently, several regulating controllers were proposed for task space to overcome parametric uncertainties [8]. The approximate Jacobian controllers were proposed with task-space damping for the set-point control of robot with uncertain kinematics and dynamics [9]. And, an adaptive Jacobian controller was proposed for trajectory tracking control of robot manipulators in task-space under parametric uncertainties [10]. The controller does not require exact knowledge of Jacobian matrix and dynamic parameters. Moreover, an adaptive task-space tracking control method was proposed using visual task-space information to overcome the parametric uncertainties in model including actuators [3]. Thus, adaptive control of robot in task-space is successful to overcome parametric uncertainties, however unstructured uncertainties are remained to consider.

The robust control approaches can present the uniform bounded error convergence in the case of wide range of uncertainties. This is a result of uniform ultimate boundedness (u.u.b.) of the tracking error using the Lyapunov based theory of guaranteed stability of uncertain system [11-12]. The u.u.b. of the tracking error will not result in a perfect tracking performance such as asymptotic stability.

In this paper, a new nonlinear robust control is proposed for trajectory tracking of robot with uncertain kinematics and dynamics. Simulation results are presented to illustrate the performance of the proposed controller.

Problem Formulation in joint space

The dynamics of the robot with n degree of freedom can be expressed as [6]

$$M(q)\ddot{q} + V_m(q,\dot{q})\dot{q} + G(q) + F_d\dot{q} + F_s(\dot{q}) + T_d = \tau(t), \tag{1}$$

where $q(t) \in R^n$ denotes the joint angles of the manipulator; $\dot{q}(t)$ and $\ddot{q}(t)$ are the vectors of joint velocity and joint acceleration, respectively. $M(q) \in R^{n\times n}$ is the inertia matrix which is symmetric and positive definite, $V_m(q,\dot{q})\dot{q} \in R^n$ is a vector function containing coriolis and centrifugal forces, $G(q) \in R^n$ is a vector function consisting of gravitational forces. $F_d \in R^{n\times n}$ is a diagonal matrix of viscous and dynamic friction coefficients, $F_s(\dot{q}) \in R^n$ is the vector of unstructured friction effects such as static friction terms. $T_d \in R^n$ is the vector of any generalized input due to disturbances or un-modeled dynamics, $\tau(t) \in R^n$ is the vector function consisting of applied generalized torques. For simplicity of (1), $H(q,\dot{q})$ can be shown as:

$$H(q,\dot{q}) = V_m(q,\dot{q})\dot{q} + G(q) + F_d\dot{q} + F_s(\dot{q}) + T_d. \quad (2)$$

By substituting Eq (2) into (1), we have:

$$M(q)\ddot{q} + H(q,\dot{q}) = \tau(t). \quad (3)$$

In the presence of uncertainty such as unknown parameters, frictions, load variation, disturbances and un-model dynamics, dynamics of robot manipulator in (3) are usually not totally known. All the terms in Eq (3) can be reduced into two parts, without loss of any generality:

$$\begin{cases} M(q) = M_k(q) + M_u(q), \\ H(q,\dot{q}) = H_k(q,\dot{q}) + H_u(q,\dot{q}), \end{cases} \quad (4)$$

where

$$H_k(q,\dot{q}) = V_{m,k}(q,\dot{q})\dot{q} + G_k(q) + F_{d,k}\dot{q},$$
$$H_u(q,\dot{q}) = V_{m,u}(q,\dot{q})\dot{q} + G_u(q) + F_{d,u}\dot{q} + F_s(\dot{q}) + T_d, \quad (5)$$

where $M_k(q)$, $H_k(q,\dot{q})$, $V_{m,k}(q,\dot{q})$, $G_k(q)$ and $F_{d,k}$ are the known parts and $M_u(q)$, $H_u(q,\dot{q})$, $V_{m,u}(q,\dot{q})$, $G_u(q)$ and $F_{d,u}$ denote the unknown parts of $M(q)$, $H(q,\dot{q})$, $V_m(q,\dot{q})$, $G(q)$ and F_d respectively. To design nonlinear robust controller, the following assumptions should be established.

Assumptions

1. $\underline{m} I_n \le M(q) \le \overline{m}(q) I_n \quad ,\forall q \in R^n$;
2. $\|V_m(q,\dot{q})\| \le \xi_c(q)\|\dot{q}\| \quad , \forall q,\dot{q} \in R^n$;
3. $\|F_d y + F_s(y)\| = \xi_{f_0} + \xi_{f_1}\|y\| \ ,\forall y \in R^n$;
4. $\|G(y)\| \le \xi_g(y) \ ,\forall y \in R^n$;
5. $\|T_d\| \le \xi_t$;

where $\underline{m}$, ξ_{f_0}, ξ_{f_1} and ξ_t are positive constant and assumed to be known constants. $\overline{m}(q)$ and $\xi_c(q)$ are known, positive definite function of q and ξ_g is a known positive definite function. For a revolute- joint robot, matrix $M(q)$ is not only positive definite but also its dependence on q is in the form of the trigonometric functions, sine and cosine. This implies that, for revolute-joint robots, $\overline{m}(q) = \overline{m}$, $\xi_c(q) = \xi_c$ and $\xi_g(q) = \xi_g$ are all constants.

Control input in joint space

By substituting Eq.(4) into (3), We have:

$$(M_k(q) + M_u(q))\ddot{q} + (H_k(q,\dot{q}) + H_u(q,\dot{q})) = \tau(t). \quad (6)$$

We define position error $e(t) = q_d - q$ and velocity error $\dot{e}(t) = \dot{q}_d - \dot{q}$ in joint space. According to Eq.6, we propose control law to following form:

$$\tau(t) = M_k(q)\ddot{q}_d + H_k(q,\dot{q}) - \alpha\, e(t) - k\,\dot{e}(t) + u_r, \quad (7)$$

where $\ddot{q}_d \in R^n$ is desired joint acceleration, α and k are positive constant and u_r is new robust control law. (7) is substituted into (6) and it can be simplified as:

$$\ddot{e}(t) = M_k^{-1}(q)(M_u(q)\ddot{q} + H_u(q,\dot{q}) + \alpha\, e(t) + \\ + k\,\dot{e}(t) - u_r). \quad (8)$$

We define following equation:

$$\Delta A = M_u(q)\ddot{q} + H_u(q,\dot{q}) + \alpha\, e(t) + k\,\dot{e}(t). \quad (9)$$

Since all of the joints are revolute and by according to assumptions (1)–(5), we have:

$$\|\Delta A\| \le \|\overline{m}\|\|\ddot{q}_d\| + \xi_c\|\dot{q}\|^2 + \xi_g + \xi_{f_0} + \xi_{f_1}\|\dot{q}\| + \xi_t + \\ + \alpha\|e(t)\| + k\|\dot{e}(t)\|. \quad (10)$$

We can express Eq.(10) to the following form:

$$\|\Delta A\| \le \beta + \alpha\|e(t)\| + k\|\dot{e}(t)\|, \quad (11)$$

where β is positive constant. By defining $e(t) = X_1(t)$ and $\dot{e}(t) = X_2(t)$, (8) can be expressed as:

$$\begin{cases} \dot{X}_1(t) = X_2(t), \\ \dot{X}_2(t) = M_k^{-1}(q)(\Delta A - u_r). \end{cases} \quad (12)$$

Closed loop system (12) can be controlled by backstepping method, therefore we can select $X_2(t)$ as control law until $X_1(t)$ converges to zero [13]. Thus we propose $X_2(t)$ as:

$$X_2(t) = -\mu X_1(t), \quad (13)$$

where μ is positive constant. For stability proof, candidate Lyapunov function is suggested as:

$$V_1(X_1) = \frac{1}{2}X_1^T(t)X_1(t). \quad (14)$$

The time derivative of (14) is

$$\dot{V}_1(X_1) = \dot{X}_1^T(t)X_1(t). \quad (15)$$

Substituting (12) and (13) into (15) results in:

$$\dot{V}_1(X_1) = -\mu X_1^T(t)X_1(t). \quad (16)$$

(16) shows that $\dot{V}_1(X_1) \leq 0$,therefore $X_1(t)$ converges to zero.

Closed loop stability proof

For stability proof of closed loop system (12), we proposed candedate lyaponov function as:

$$V_2(X_1, X_2) = \frac{1}{2} X_1^T(t) X_1(t) + \\ + \frac{1}{2}(X_2(t) + \mu X_1(t))^T (X_2(t) + \mu X_1(t)). \quad (17)$$

The time derivative of (17) is

$$\dot{V}_2(X_1, X_2) = \dot{X}_1^T(t) X_1(t) + \\ + (\dot{X}_2(t) + \mu \dot{X}_1(t))^T (X_2(t) + \mu X_1(t)). \quad (18)$$

(12) and (13) are substituted into (18) as:

$$\dot{V}_2(X_1, X_2) = -\mu X_1^T(t) X_1(t) + \\ + (M_k^{-1}(q)(\Delta A - u_r) + \mu X_2(t))^T (X_2(t) + \mu X_1(t)). \quad (19)$$

(19) can be simplified as:

$$\dot{V}_2(X_1, X_2) = -\mu \|X_1(t)\|^2 + (M_k^{-1}(q)\Delta A)^T \times \\ \times (X_2(t) + \mu X_1(t)) + (\mu X_2(t) - M_k^{-1}(q) u_r)^T \times \\ \times (X_2(t) + \mu X_1(t)). \quad (20)$$

According to assumptions 1-5, we can express (20) as:

$$\dot{V}_2(X_1, X_2) \leq -\mu \|X_1(t)\|^2 + \left\| \underline{m}^{-1} \right\| \|\Delta A\| \times \\ \times \|X_2(t) + \mu X_1(t)\| + (\mu X_2(t) - M_k^{-1}(q) u_r)^T \times \\ \times (X_2(t) + \mu X_1(t)). \quad (21)$$

According to (21), robust control law u_r can be suggested as:

$$u_r = M_k(q) \mu X_2(t) + \gamma M_k(q)(X_2(t) + \mu X_1(t)), \quad (22)$$

where γ is positive constant. Substituting (22) into (21) results in :

$$\dot{V}_2(X_1, X_2) \leq -\mu \|X_1(t)\|^2 + \\ + \left\| \underline{m}^{-1} \right\| \|\Delta A\| \|X_2(t) + \mu X_1(t)\| - \\ - \gamma \|X_2(t) + \mu X_1(t)\|^2. \quad (23)$$

According to (11), (12), (13) and (23), we have:

$$\dot{V}_2(X_1, X_2) \leq -\mu \|X_1(t)\|^2 + \left\| \underline{m}^{-1} \right\| \varepsilon \|X_1(t)\| + \\ + \left\| \underline{m}^{-1} \right\| \lambda \|X_1(t)\|^2 - \gamma \|X_2(t) + \mu X_1(t)\|^2, \quad (24)$$

where ε and λ are positive constant. According to (22) and (24), μ and γ are coefficient of controller. So we can guarantee $\dot{V}_2(X_1, X_2) \leq 0$ by properly selecting these coefficients. Thus closed loop system (12) is global asymptotic stable by using proper control coefficients. The joint space control law follows as:

$$\begin{cases} \tau(t) = M_k(q)\ddot{q}_d + H_k(q, \dot{q}) - \alpha e(t) - k \dot{e}(t) + u_r, \\ u_r = M_k(q) \mu \dot{e}(t) + \gamma M_k(q)(\dot{e}(t) + \mu e(t)). \end{cases} \quad (25)$$

Robust backstepping control in task space

Closed loop system (12) is global asymptotic stable using the joint space control law (25), but according to the introduction section, precise trajectory tracking of robot manipulator cannot be guaranteed using the control law (25) in task space. Therefore, we will generalize robust backstepping control in joint space to task space in this section.

We know that Robot dynamics in task space follows as:

$$\begin{cases} A(q)\ddot{X} + N(q, \dot{q}) = f(t), \\ A(q) = J^{-T}(q) M(q) J^{-1}(q), \\ N(q, \dot{q}) = J^{-T}(q) H(q, \dot{q}) - \\ - J^{-T}(q) M(q) J^{-1}(q) \dot{J}(q) \dot{q}. \end{cases} \quad (26)$$

In the presence of uncertainties, dynamics of robot manipulator in (26) are usually not totally known. All the terms in Eq (26) can be reduced into two parts:

$$\begin{cases} A(q) = A_k(q) + A_u(q), \\ A_k(q) = J^{-T}(q) M_k(q) J^{-1}(q), \\ N(q, \dot{q}) = N_k(q, \dot{q}) + N_u(q, \dot{q}), \\ N_k(q, \dot{q}) = J^{-T}(q) H_k(q, \dot{q}) - \\ - J^{-T}(q) M_k(q) J^{-1}(q) \dot{J}(q) \dot{q}, \end{cases} \quad (27)$$

where $A_k(q)$, $M_k(q)$, $N_k(q, \dot{q})$ and $H_k(q, \dot{q})$ are the known parts and $A_u(q)$ and $N_u(q, \dot{q})$ denote the unknown parts of $A(q)$, $M(q)$, $N(q, \dot{q})$ and $H(q, \dot{q})$ respectively.

According to the previous sections, we can proof that system (26) are global asymptotic stable with following task space control law:

$$\begin{cases} f(t) = A_k(q)\ddot{X}_d + N_k(q, \dot{q}) - \alpha e(t) - k \dot{e}(t) + u_r, \\ u_r = A_k(q) \mu \dot{e}(t) + \gamma A_k(q)(\dot{e}(t) + \mu e(t)), \\ e(t) = X_d - X \quad , \; \dot{e}(t) = \dot{X}_d - \dot{X}, \end{cases} \quad (28)$$

where α, k, μ and γ are positive constants, $\ddot{X}_d$ is desired task space acceleration, $e(t)$ and $\dot{e}(t)$ are position and velocity errors in the task space, respectively. For stability proof, we suggest candidate Lyapunov functions (14) and (17).

Modifying the Control Law in task space

Sensing requirements is another important problem which should be considered. The control law (28) is formed by measuring joint positions q, the joint velocities $\dot{q}$ and the end-effector positions X and the end-effector velocities $\dot{X}$. A joint position is commonly measured by an optical encoder and a joint velocity may be measured directly or by soft derivative of joint position and many commercial sensors are available for measurement of X, such as vision systems, electromagnetic measurement systems, position sensitive detectors or laser tracking systems. However, $\dot{X}$ is rarely measured in robotic applications while vision technique can be used for this purpose. Alternatively, vision technique was used to measure the end-effector position X precisely and then $\dot{X}$ can be computed. For sake of practical purposes, (28) can be modified as

$$\begin{cases} f(t) = A_k(q)\ddot{X}_d + N_k(q,\dot{q}) - \alpha e(t) - k\dot{e}(t) + u_r, \\ u_r = A_k(q)\mu\dot{e}(t) + \gamma A_k(q)(\dot{e}(t) + \mu e(t)), \\ e(t) = X_d - X \;\;, \dot{e}(t) = \dot{X}_d - \hat{J}(q)\dot{q}, \\ A_k(q) = \hat{J}^{-T}(q)M_k(q)\hat{J}^{-1}(q), \\ N_k(q,\dot{q}) = \hat{J}^{-T}(q)H_k(q,\dot{q}), \\ -\hat{J}^{-T}(q)M_k(q)\hat{J}^{-1}(q)\dot{\hat{J}}(q)\dot{q}, \end{cases} \tag{29}$$

where $\hat{J}(q)$ is an estimation of Jacobian matrix. Control law (29) is formed by measuring joint positions q, the joint velocities $\dot{q}$ and the end-effector positions X. Thus control law (29) with respect to (28) is more practical. But in the presence of imperfect Jacobian matrix, we have velocity computation error in (29), Therefore closed loop system has uniform ultimate boundedness stablity using control law (29). To reduce production cost in control law (29), we can compute position errors using velocity errors. Thus control law (29) can be modified as:

$$\begin{cases} f(t) = A_k(q)\ddot{X}_d + N_k(q,\dot{q}) - \alpha e(t) - k\dot{e}(t) + u_r, \\ u_r = A_k(q)\mu\dot{e}(t) + \gamma A_k(q)(\dot{e}(t) + \mu e(t)), \\ \hat{e}(t) = \int \dot{\hat{e}}(t)dt \;\;, \dot{\hat{e}}(t) = \dot{X}_d - \hat{J}(q)\dot{q}, \\ A_k(q) = \hat{J}^{-T}(q)M_k(q)\hat{J}^{-1}(q), \\ N_k(q,\dot{q}) = \hat{J}^{-T}(q)H_k(q,\dot{q}) - \\ -\hat{J}^{-T}(q)M_k(q)\hat{J}^{-1}(q)\dot{\hat{J}}(q)\dot{q}. \end{cases} \tag{30}$$

To apply (30), we need to measure joint positions q and the joint velocities $\dot{q}$. Although closed loop system has uniform ultimate boundedness stability using control law (30), but trajectory tracking error in task space is controllable. Because, we have:

$$\begin{cases} \dot{e}(t) = \dot{X}_d - \dot{X}\,, \; \dot{\hat{e}} = \dot{X}_d - \hat{J}(q)\dot{q}, \\ \dot{e}(t) = \mu e(t), \dot{\hat{e}} = \mu\hat{e}(t), \\ \dot{\hat{e}}(t) - \dot{e}(t) = \mu(\hat{e}(t) - e(t)) = \dot{X} - \hat{J}(q), \\ (\hat{e}(t) - e(t)) = \mu^{-1}(\dot{X} - \hat{J}(q)). \end{cases} \tag{31}$$

According to (31), tracking error in task space is reduced by increasing of control coefficient μ.

Case Study of Two-Link Elbow Robot Manipulator

In order to verify the performance of proposed control schemes, as an illustration, we will apply the above presented controllers to a two-link elbow robot manipulator shown in figure1. The dynamic of the two-link elbow robot manipulator can be described in the following differential equation [6] :

$$\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}\ddot{q} + V_m(q,\dot{q})\dot{q} + G(q) + B\dot{q} + F_d\dot{q} + \\ + F_s + T_d = \tau(t), \tag{32}$$

$$M_{11} = m_1 l_{c_1}^2 + m_2(l_1^2 + l_{c_2}^2 + 2l_1 l_{c_2}\cos(q_2)) + I_1 + I_2, \tag{33}$$

$$M_{12} = M_{21} = m_2\left(l_{c_2}^2 + l_1 l_{c_2}\cos(q_2)\right) + I_2, \tag{34}$$

$$M_{22} = m_2 l_{c_2}^2 + I_2, \tag{35}$$

$$V(q,\dot{q}) = \begin{bmatrix} -m_2 l_1 l_{c_2}\dot{q}_2\sin(q_2) & -m_2 l_1 l_{c_2}(\dot{q}_1 + \dot{q}_2)\sin(q_2) \\ m_2 l_1 l_{c_2}\dot{q}_1\sin(q_2) & 0 \end{bmatrix}, \tag{36}$$

$$G(q) = \begin{bmatrix} (m_1 l_{c_1} + m_2 l_1)g\cos(q_1) + m_2 l_{c_2} g\cos(q_1 + q_2) \\ m_2 l_{c_2} g\cos(q_1 + q_2) \end{bmatrix}, \tag{37}$$

$$F_d = \begin{bmatrix} F_{d_1} & 0 \\ 0 & F_{d_2} \end{bmatrix}, \tag{38}$$

$$F_s = \begin{bmatrix} F_{s_1} \\ F_{s_2} \end{bmatrix}, \tag{39}$$

$$T_d = \begin{bmatrix} T_{d_1}\sin(t) \\ T_{d_2} \end{bmatrix}, \tag{40}$$

where q_i for $i = 1,2$ denotes the joint angle, l_i is the link length, m_i is the link mass, is the link's moment of inertia given in center of mass, l_{c_i} is the distance between the center of mass of link and the ith joint, F_{d_i} is dynamic friction, F_{s_i} is static friction, T_{d_i} is disturbance and un-model dynamic and $\tau(t)$ is torque input.

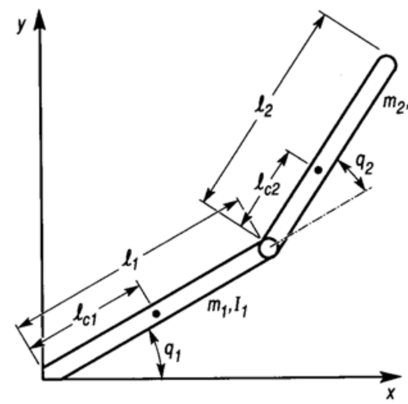

Fig. 1. Two- Link Elbow Manipulator

The Jacobian matrix is in the form of

$$J(q) = \begin{bmatrix} -l_1\sin(q_1) - l_2\sin(q_1 + q_2) & -l_2\sin(q_1 + q_2) \\ l_1\cos(q_1) + l_2\cos(q_1 + q_2) & l_2\cos(q_1 + q_2) \end{bmatrix}. \tag{41}$$

The kinematic equation is given by

$$X = \begin{bmatrix} l_1\cos(q_1) + l_2\cos(q_1 + q_2) \\ l_1\sin(q_1) + l_2\sin(q_1 + q_2) \end{bmatrix}. \tag{42}$$

The link's parameters are estimated by a gain of 0.9 from real values given in Table 1. We set the controller with $\alpha = 1$, $k = 1$ and $\mu = 20$. Then a circle with a radius of 0.5 m centered at (0.95,0.95) is given to control system as a desired trajectory. Initial condition is at (1,1).

Table 1. Parameters of Two- Link Elbow Robot

Link	L	L_C	M	I	F_s	F_d	T_d
1	1	0.5	15	5	1	1	50
2	1	005	6	2	1	1	10

Simulation Results

Sim1. the joint space control given in (25) is simulated with $\gamma = 20$ to track the circle. The performance of control system is not satisfactory as shown in Fig.2 while the norm of tracking error in task space shows a maximum value of 10 mm in Fig. 3.

Sim 2. The task space control given in (28) is simulated where the paramiters are the same as before. We cannot see any differences between the desired and actual trajectories as shown in Fig. 4. the norm of tracking error in task space has been converged to zero as shown in Fig. 5. The control inputs are under the permitted values of $40\,Nm$ as shown in Fig. 6.

Sim 3. The modified control given in (30) is simulated where the parameters are the same as before. The norm of tracking error in task space shows a maximum value of 1.5 mm in Fig. 7. We can reduce the maximum norm of tracking error by increasing control coefficients μ and γ in the modified control law (30) as shown in Fig. 8. The simulation results show norm of errors for given values of 20, 60 and 100 to μ and 40, 75 and 100 to γ, respectively.

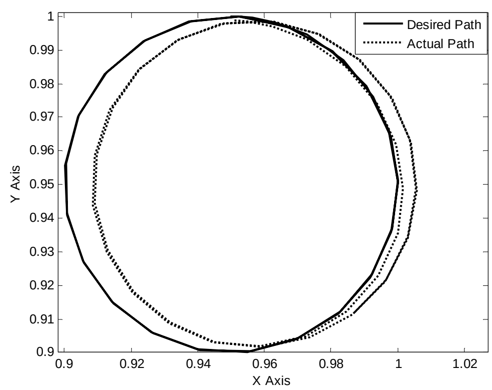

Fig. 2. Tracking a circle by control law (25)

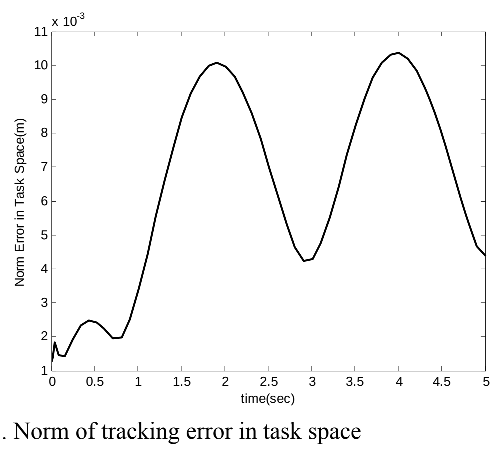

Fig. 3. Norm of tracking error in task space

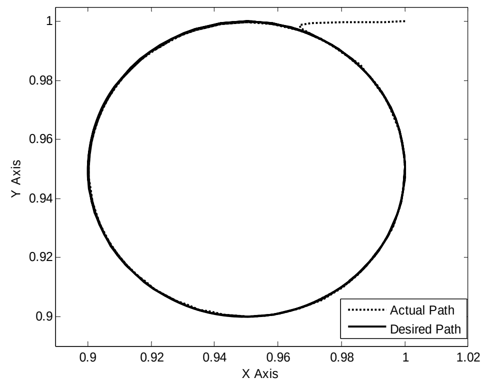

Fig. 4. Tracking a circle by control law (28)

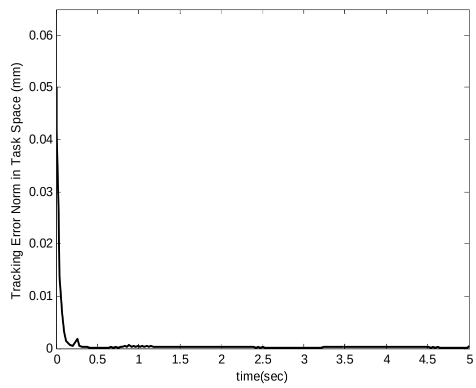

Fig. 5. Norm of tracking error in task space

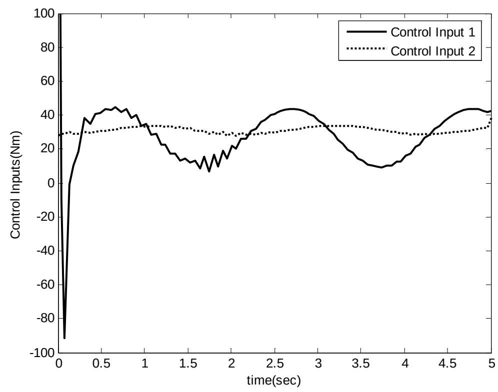

Fig. 6. Control inputs in task space control

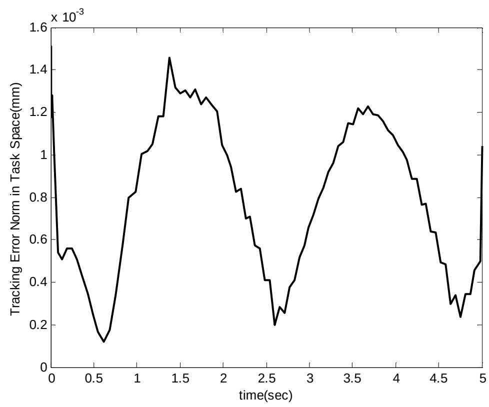

Fig. 7. Norm of tracking error in task space

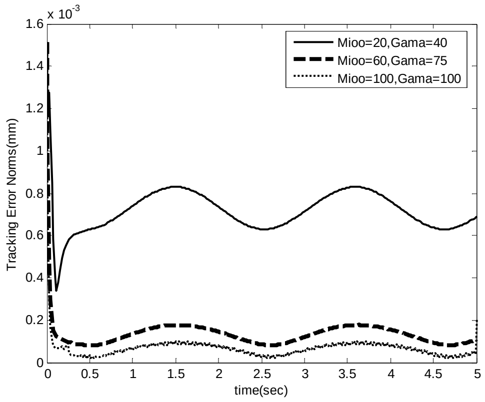

Fig. 8. Increasing control coefficients reduces tracing error

Conclusion

A novel approach was developed for trajectory tracking control of robotic manipulators in task space. The simulation results confirmed that the proposed control law can provide a desired tracking performance for a robotic manipulator with uncertain dynamics and uncertain kinematics. It is concluded that the proposed approach can be used for task-space tracking control of a normal-cost due to overcoming uncertainties. In contrast, a perfect joint space control approach will never provide a desired tracking performance in task space for such a robot. Moreover, applying feedback linearization technique without realizing and canceling the uncertainties cannot operate well. The modifications were presented to simplify sensing problem such that the control law to be free of positions and velocities of end-effctor.

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M. R. Soltanpour, S. E. Shafiei. Robust Backstepping Control of Robot Manipulator in Task Space with Uncertainties in Kinematics and Dynamics // Electronics and Electrical Engineering. – Kaunas: Technologija, 2009. – No. 8(96). – P. 75–80.

This paper introduces a novel robust control approach for trajectory tracking of robot manipulator in task space. A new task space control scheme is proposed to overcome the uncertainties in robot dynamics and kinematics. A robust controller is designed based on Lyapunov method, using backstepping method. It is then proven that the closed loop system has global uniform ultimate boundedness stability. Modifications are given to derive a control law which is free of position and velocity of end-effector. The control approach is applied on a two-links elbow robot manipulator. The performance of proposed control laws are confirmed by simulations. Ill. 8, bibl. 13, tabl. 1 (in English; abstracts in English, Russian and Lithuanian).

М. Р. Солтанпур, С. Э. Шафей. Исследование контроля манипулятора робота в заданном пространстве с неопределенными кинематикой и динамикой // Электроника и электротехника. – Каунас: Технология, 2009. – № 8(96). – С. 75–80.

Рассмотрен новый метод контроля слежения манипулятора робота в заданном пространстве. Предложена схема контроля заданного пространства, которая учитывает неясности, связанные с динамикой и кинематикой робота. Управляющий механизм создан с использованием метода Ляпунова. Доказано, что система замкнутого цикла имеет ограниченную стабильность. Приведены способы преобразования в системе контроля, которые обладают независимостью от положения и скорости. Результаты исследований контроля внедрены при организации двухмерного управления кулисой манипулятора робота. Ил. 8, библ. 13, табл. 1 (на английском языке; рефераты на английском, русском и литовском яз.).

M. R. Soltanpour, S. E. Shafiei. Roboto manipuliatoriaus kontrolės tyrimas pasirinktoje neapibrėžtos kinematikos ir dinamikos erdvėje // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009. – Nr. 8(96). – P. 75–80.

Apžvelgtas naujas metodas roboto manipuliatoriaus sekimo kontrolei tirti pasirinktoje erdvėje. Pasiūlyta pasirinktos erdvės kontrolės schema, kuri įvertina neaiškumus, susijusius su roboto dinamika ir kinematika. Valdiklis yra sukurtas remiantis Liapunovo metodu. Įrodyta, kad uždaro ciklo sistema yra riboto stabilumo. Pateikti kontrolės sistemos keitimo būdai, kurie yra nepriklausomi nuo padėties ir greičio veiksnių. Kontrolės tyrimo rezultatai panaudoti dvilaipsniam roboto manipuliatoriaus alkūnės valdymui. Il. 8, bibl. 13, lent. 1 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).