International Journal of Control Science and Engineering 2017, 7(1): 18-23
DOI: 10.5923/j.control.20170701.03

Model Reference Adaptive Control for Robot Tracking Problem: Design & Performance Analysis

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Abstract In this paper, robots tracking problem with the known and unknown parameters in the presence of torque disturbances are addressed. For addressing this challenge, a controller is designed for tracking the desired path of the robot's angle. With applying an adaptive controller Jacobian matrix is estimated and updated. Therefore, the tracking error will be reduced and converges to the reference model. The simulation results show the effectiveness of the proposed methods.

Keywords Model reference, Adaptive control, Robot, Jacobian matrix, Torque disturbance, Unknown parameter, Known parameter

1. Introduction

Todays, needs of industries to high precision design, implementation of robots with accurate programming ability, minimum time delay and robust stability of robots are increased [1, 2]. In industries, fixed robots are widely used. The fixed robots can be used in many purposes such as the assembly, painting, welding, and placement of components on the printed circuit board and pieces. Because of the importance of the first and the last track of these types of robots, the point to point control method is very applicable in this regard [3, 4, 19].

Various methods are used for controlling the motion of robot's arm and achieve to the minimum tracking error. One type of these controllers is model reference adaptive control (MRAC). In this type of control approach, the feedback controller and an auxiliary signal are used to enhance the stability of the closed loop system and reach to optimal path [5, 6].

Although, this method has advantages such as is not difficult for implementing of complex nonlinear systems and, it has quick adaption respect to the unknown disturbances, the adaptation has practical difficulties and path tracking is associated with an error. In order to solve this problem, the robust adaptive controller is employed. In this scheme, by considering the uncertainty due to the linearization of equations and existence of disturbances on the body of the robot, the robot's arm motion action takes place, and the best route will be accessed by minimum error [7, 8]. In this condition, obtaining a Lyapunov function and considering parameters uncertainty for stability analysis of system is difficult. Therefore, PID controller is proposed to increase its stability and compensate steady state error [10, 11]. In this condition, the disturbances of system will be strengthened, and will be caused to be weakened in the path tracking. For solving this problem, in [9], a fuzzy PID controller is proposed. In this method, PID parameters are supervised by fuzzy logic, but disturbance rejection in this controller is difficult.

In the previous studies on this kind of robots, the external and internal disturbances on the robot with known variables was considered and based on this fact and using different controllers such as adaptive control, the position of robot's angle was controlled [12].

In this paper, an exogenous disturbance in the robot and its influence on 2 degrees freedom robot performance with both unknown dynamic parameters and kinetic will be presented. To the best of authors knowledge not much attempt have been made on this problem. Considering these conditions, a model reference adaptive control is introduced.

The rest of the paper is organized as follows: the dynamic equation of two degrees of freedom with known parameters is given in the section 2. The dynamic and kinetic equations of the robot with unknown parameters and estimates expressed Jacobian to obtain the unknown parameters in section 3, and adaptive control is designed. A comparative simulation study of robot with known and unknown robot is demonstrated in section 4 to show the effectiveness of the proposed algorithm. Finally, the conclusions are given in section 5.

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Published online at http://journal.sapub.org/control

2. Robot Dynamic Equation

The dynamic equation of a 2-link robotic manipulator are described as [13]:

$$M(q)\ddot{q}+(\frac{1}{2}\dot{M}(q)+S(q,\dot{q}))\dot{q}+g(q)=\tau \quad (1)$$

where $M(q)$ is the inertial matrix, and it is symmetric and positive definite. $q=[q_1,q_1,...,q_n]^T$ is a vector of joint position; $S(q,\dot{q})$ shows the effect of torsion and centrifugal force that is symmetric and positive definite matrix. $g(q)$ represents the gravity force which it is assumed is equal to $9.8\frac{m}{s^2}$. τ represents the torque input vectors of each joint that in this paper, it is considered as a control input.

The equations of the robot with two degrees of freedom can be rewritten as the following form [12]:

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} +\frac{1}{2}(\begin{bmatrix} \dot{m}_{11} & \dot{m}_{12} \\ \dot{m}_{21} & \dot{m}_{22} \end{bmatrix}+\begin{bmatrix} -c & -c(\dot{q}_1+\dot{q}_2) \\ c\dot{q}_1 & 0 \end{bmatrix})\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} +\begin{bmatrix} g_1(q_1+q_2) \\ g_2(q_1+q_2) \end{bmatrix}=\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \quad (2)$$

The torque input is defined as

$$\tau = y_d(q,\dot{q},\ddot{q})\theta_d \quad (3)$$

In the above equation, matrix $y_d(q,\dot{q},\ddot{q})$ represents a dynamic regression matrix, and θ_d is $\theta_d=[\theta_{d1},\theta_{d2},...,\theta_{dn}]$, and it shows the dynamic parameters of robot. According to equation (2) the equation of system can be considered in the following form:

$$M(q)\ddot{q}+(\frac{1}{2}\dot{M}(q)+S(q,\dot{q}))\dot{q}+g(q)=y_d(q,\dot{q},\ddot{q})\theta_d \quad (4)$$

The desired path for the robot's joint has been found in the workplace. This path can be in the projective space or Cartesian coordinates form. If x is a vector in workspace, $\dot{x}$ will be the speed vector in workspace. If the camera is used to monitor the position of the joint, workspace will be visual and in terms of pixels, and if the sensor is used to monitor the position, the workspace will be based on the Cartesian coordinates.

$$\theta_k=[\theta_{k1},\theta_{k2},...,\theta_{kq}]^T \quad (5)$$

Therefore, to calculate the x vector can be used from the following equation:

$$\dot{x}=y_k(q,\dot{q})\theta_k \quad (6)$$

The Initial modeling of robot can be done in several ways that in the all procedures should be expressed link between joint space and work space. This relation is established by the Jacobins matrix, thus the dynamic, kinematic and the stimulus of system and the robot is concerned. Based on the previous description, the equation (6) can be rewritten in the following form [14]:

$$\dot{x}=J(q)\dot{q}=y_k(q,\dot{q})\theta_k \quad (7)$$

In the above equation, $J(q)$ represents the Jacobian matrix that is full order, and it is [15]:

$$J(q)=\begin{bmatrix} -l_1s_1-l_2s_{12} & -l_2s_{12} \\ l_1c_1+l_2c_{12} & l_2s_{12} \end{bmatrix} \quad (8)$$

After the description of robot equations, in the next section, the controller will be designed. Adaptive control can be divided into two methods: direct and indirect which in this paper, both methods are analyzed [13, 16].

3. Influence of Disturbance on a Robot

In this section, the impact of disturbance on a 2 degree of freedom robot is addressed. In the most previous researches like [6-13, 15] the robot gripper tracks the desired trajectory in normal condition without any internal or external disturbances, and design and evaluate the stability of the robot controller in the presence of disturbance is not considered. Motivating by above discussion, in this paper, robots with unknown parameters in the presence of disturbance is considered and the input torque is affected by an exogenous disturbance. Figure 1 shows the block diagram of reference model adaptive control with torque disturbance.

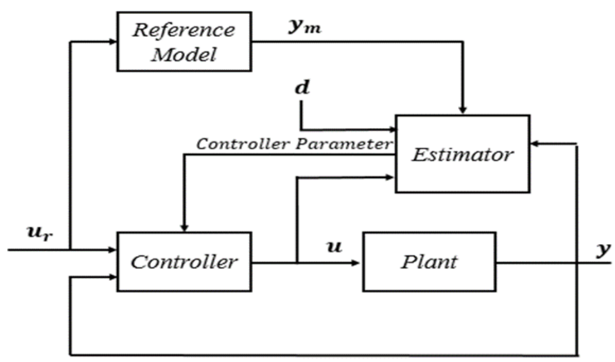


Figure 1. Block diagram of model reference adaptive control with an exogenous disturbance

The dynamic equation of robot in presence of disturbance is defined as:

$$M(q)\ddot{q}+(\frac{1}{2}\dot{M}(q)+S(q,\dot{q}))\dot{q}+g(q)+\tau_d=\tau \quad (9)$$

Where τ_d is torque disturbance in the robot. In order to modelling this disturbance, an input pulse with value of $10\frac{m}{s^2}$ and width equal to 0.4 second sis considered. This disturbance is exposed to the body of robot from torque input.

The parameters of the Jacobian matrix is uncertain, the following dynamic approximator model is used:

$$\hat{\dot{x}} = \hat{J}(q,\hat{\theta}_k)\dot{q} = y_k(q,\dot{q})\hat{\theta}_k \quad (10)$$

$\hat{J}(q,\hat{\theta}_k)$ is an approximate Jacobian matrix and is [13]:

$$\hat{J}(q,\hat{\theta}_k) = \begin{bmatrix} \hat{l}_1 s_1 - \hat{l}_2 s_{12} & -\hat{l}_2 s_{12} \\ \hat{l}_1 c_1 - \hat{l}_2 c_{12} & \hat{l}_2 s_{12} \end{bmatrix} \quad (11)$$

The model of equation (12) can be rewritten in the following form [17]:

$$\hat{\dot{x}} = \begin{bmatrix} -s_1\dot{q}_1 & -s_{12}(\dot{q}_1+\dot{q}_2) \\ -c_1\dot{q}_1 & -c_{12}(\dot{q}_1+\dot{q}_2) \end{bmatrix} \begin{bmatrix} \hat{l}_1 \\ \hat{l}_2 \end{bmatrix} = y_k(q,\dot{q})\hat{\theta}_k \quad (12)$$

To avoid the need for measuring task-space velocity in adaptive Jacobian tracking control, we introduce a known signal y:

$$\dot{y} + \lambda y = \lambda \dot{x} \quad (13)$$

where, λ is known, and the signal y can be computed by measuring x alone, and by using (7) and (13) we have

$$y = \frac{\lambda p}{p+\lambda} x = W_k(t)\theta_k \quad (14)$$

where p is the Laplace operator, and $W_k(t)$ is defined as follows:

$$W_k(t) = \frac{\lambda}{p+\lambda} y_k(q,\dot{q}) \quad (15)$$

The algorithm we shall now derive is composed of a control law:

$$\tau = \hat{J}^T(q,\hat{\theta}_k)(k_v\Delta\dot{x} + k_p\Delta x) - \hat{J}^T(q,\hat{\theta}_k)k\hat{s}_x + y_d(q,\dot{q},\dot{q}_r,\ddot{q}_r)\hat{\theta}_d \quad (16)$$

$$\hat{s}_x = Y_k(q,\dot{q})\hat{\theta}_k - \dot{x}_r \quad (17)$$

$$\dot{x}_r = \dot{x}_d - \alpha(x - \dot{x}_d) \quad (18)$$

$$\dot{q}_r = \hat{J}^{-1}(q,\hat{\theta}_k)\dot{x}_r \quad (19)$$

where $\hat{J}^{-1}(q,\hat{\theta}_k)\dot{x}_r$ is inverse of Jacobian matrix, $k \in R^{n\times n}$ is positive definite function. Parameter x is real vector that is approximated by examination model, and x_d is desired path. In above equation, Δx is error of tracking, and is $\Delta x = x - x_d$.

In order to calculate $y_d(q,\dot{q},\dot{q}_r,\ddot{q}_r)\hat{\theta}_d$ in equation (18), two adaption laws are used. By using these laws, the dynamic and kinetic parameters of robot can be estimated [15].

$$\dot{\theta}_d = -L_d \overline{y}_d(q,\dot{q},\dot{q}_r,\hat{\ddot{q}}_r,\hat{\theta}_k)s \quad (20)$$

and $\overline{y}_d(q,\dot{q},\dot{q}_r,\hat{\ddot{q}}_r,\hat{\theta}_k)$ is:

$$\overline{y}_d(q,\dot{q},\dot{q}_r,\hat{\ddot{q}}_r,\hat{\theta}_k) = \begin{bmatrix} y_{11} & y_{12} & y_{13} & y_{14} & y_{15} \\ 0 & y_{22} & y_{23} & 0 & y_{25} \end{bmatrix} \quad (21)$$

Adaption laws for kinetic parameters is:

$$\hat{\dot{\theta}} = -L_k W_k(t)k_v(W_k(t)\hat{\theta}_k - y) + L_k y_k^T(q,\dot{q})(k_p + \alpha k_v)\Delta x \quad (22)$$

the overall model of robot using adaption laws obtained as:

$$M(q)\dot{s} + (\frac{1}{2}\dot{M}(q) + S(q,\dot{q}))s + M(q)\hat{\ddot{q}}_r + (\frac{1}{2}\dot{M}(q) + S(q,\dot{q}))\dot{q}_r + g(q) + \tau_d = \tau \quad (23)$$

$$s = \dot{q} - \dot{q}_r = \hat{J}^{-1}(q,\hat{\theta})\hat{s}_x \quad (24)$$

We define the following Lyapunov function candidate in order to analyze the stability [18]:

$$V = \frac{1}{2}s^T M(q)s + \frac{1}{2}\Delta\theta_d^T L_d^{-1}\Delta\theta_d + \frac{1}{2}\Delta\theta_k^T L_k^{-1}\Delta\theta_k + \frac{1}{2}\Delta x^T(k_p + \alpha k_v)\Delta x \quad (25)$$

Theorem: Closed-loop system stability for system 1 ensured if k_v or k_p in (16) and adaption law parameters in (22) are equal to zero.

Proof:

By derivative of equation (23), we have:

$$\dot{V} = -\Delta\hat{\dot{x}}^T k_v \Delta\hat{\dot{x}} - \alpha\Delta x^T k_p \Delta x - \Delta\theta_k{}^T W_v{}^T(t)k_v W_k(t) \quad (26)$$

$$\Delta\theta_k - s^T\tau_d \quad (27)$$

Based on equations (17) and (18), and Lemma, $s^T\tau_d$. In addition, we know $\tau_d < \tau_{d_r}$ The Lyapunov function is negative. M(q) based on equation (1), is defined as a positive definite matrix. If $\Delta x, \Delta\theta_d$, and $\Delta\theta_k$ have limited value, therefore, value of V will be limit too. In order to evaluate the limitation of Δx, Barbalat Lemma is used. Because M(q) is positive definite and V is based on $\Delta x, \Delta\theta_d$, and $\Delta\theta_k$, therefore V is positive definite. In addition, $\dot{V} \le 0$ therefore, V is bounded and $\Delta x, \Delta\theta_d$, $\Delta\theta_k$ will be bounded. This condition that cause $\hat{\theta}_k$ and $\hat{\theta}_d$ will be bounded. Also, if x_d is bounded, x will be bounded, and $\hat{s}_x = \hat{J}(q,\hat{\theta}_k)$ will be bounded too. Therefore, we conclude if $\Delta\hat{\dot{x}}$ is bounded too.

Because Δx Δx is bounded therefore, if $\dot{x}_d$ $\dot{x}_d$ is bounded, and approximated Inverse of Jacobian matrix has limitation therefore, the bounded of $\dot{x}$ will be concluded, because Jacobian Matrix has limited value.

Remark 1: The above method not only can be used for system with unknown parameters, but also, it can be used for the systems with some known parameters too.

Remark 2: P which is a positive definite matrix, by using adaption law will be added to the equations:

$$\hat{\theta}_k = \overline{a}_k - PW_k^T(t)k_v(W(t)\hat{\theta}_k - y) + Py_k^T(q,\dot{q})(k_p + \alpha k_v)\Delta x \quad (28)$$

$$\dot{\overline{\alpha}}_k = -LW_k^T(t)k_v(W(t)\hat{\theta}_k - y) + Ly_k^T(q,\dot{q})(k_p + \alpha k_v)\Delta x \quad (29)$$

In this step, after approximation of unknown robot parameters by using Jacobian Matrix, reference model based indirect adaptive control will be designed, and controller parameters of $L(t), K(t)$ is updated based on accessed variables.

4. Simulation Results

In this section in order to show the effectiveness of our proposed controllers, simulation results on robot in presence of disturbance is shown. Figure 2 shows the step response of robot with known and unknown parameters without disturbance using the adaptive controller.

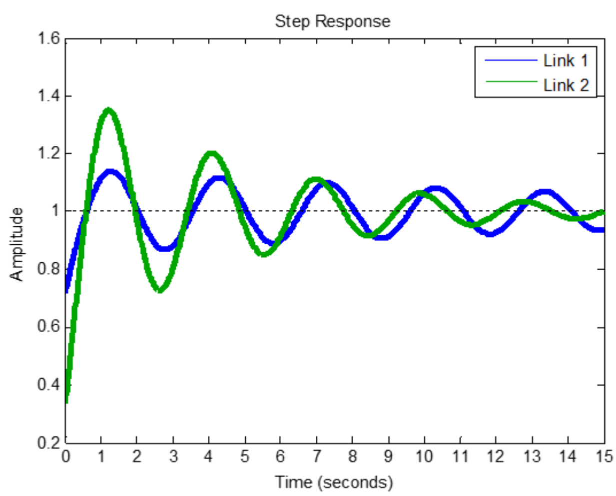
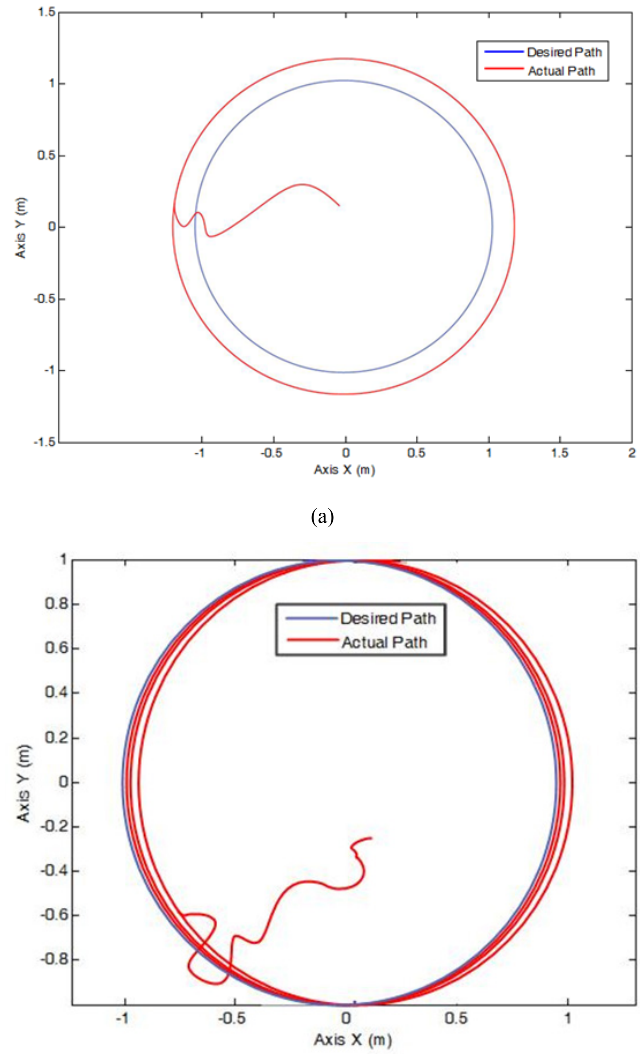


Figure 2. The transient response of robot angle with MRAC without disturbance: a) robot with known dynamic and kinetic parameters, b) robot with unknown dynamic and kinetic parameters

Figure 2(a), shows that, the system has some overshoot but after passing sometimes the settling time of link 1 is equal to 13.7 and the settling time of link 2 is equal to 12.4 and this overshot is reduced. In addition, without disturbance, the system has a steady state error and could not converge to the desired paths.

Figure 2 (b) shows with approximation of unknown robot parameters, the response has overshoot but after passing sometimes the settling time of link 1 is equal to 6.54 and the settling time of link 2 is equal to 5.2 and they could track desired path as well, although we have a little steady state error.

Figure 3 (a) shows the path of angle of robot with known dynamic and kinetic parameters. It is shown we have steady state error. The path of robot with unknown parameters is shown in figure 3(b), that the transient error is existed but it could track with very little error well.



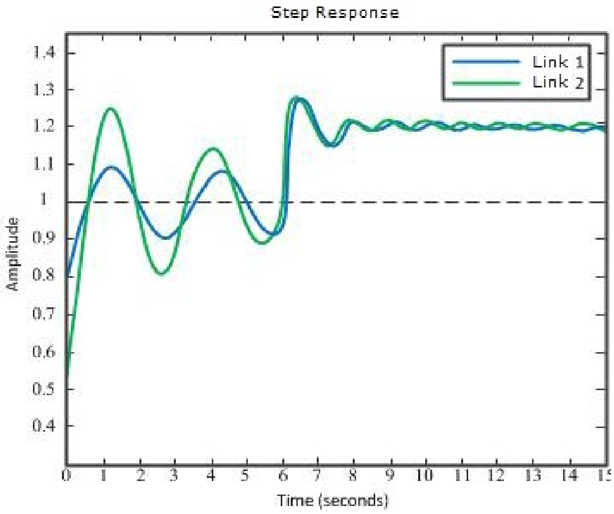
(b)

Figure 3. The path of robot angle with MRAC without disturbance: a) robot with known dynamic and kinetic parameters, b) robot with unknown dynamic and kinetic parameters

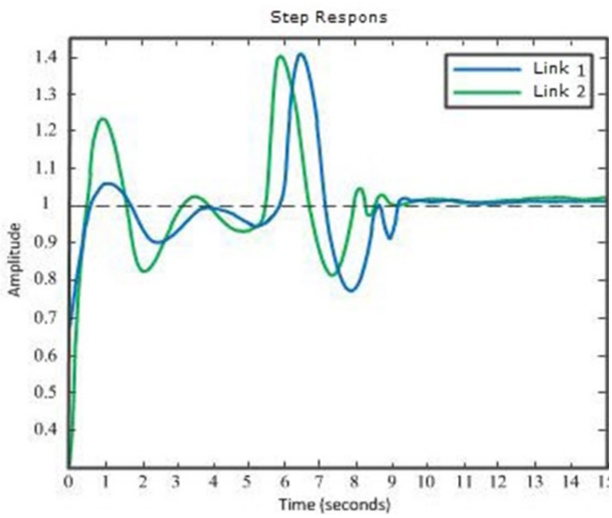
Usually, the internal and external disturbances are existed on system that influence on performance of robot and it is caused the changing in robot path.

In the following, the performance of robot in presence of disturbance will be considered. The disturbance in this paper is the torque disturbance and it is considered a pulse that exposed on system at 7 second.

Figure 4 shows the simulation results of controlling robot with known and unknown parameters in the presence of disturbance.



(a)

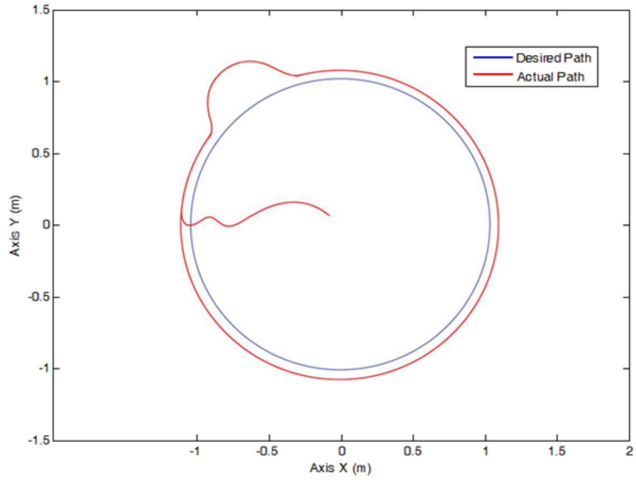


(b)

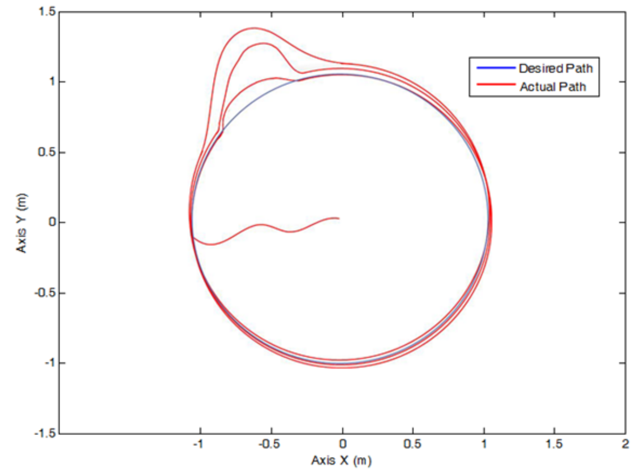
Figure 4. The transient response of robot angle with MRAC with disturbance: a) robot with known dynamic and kinetic parameters, b) robot with unknown dynamic and kinetic parameters

The effect of disturbance on robot with known equation is shown in figure 4 (a). It is shown after exposing disturbance in system, we have overshoot on 7 second, but the control is tried to reduce this overshoot, but it could not reject disturbance well. Comparing simulation results of system with disturbance and without disturbance shows that the steady state error in system with disturbance is more than system without disturbance.

Figure 4 (b) shows the response of robot with unknown parameters with disturbance. The rejection of disturbance in this system is done well. The design controller to disturbance rejection for robot with unknown parameters is better.Figures 5 (a) demonstrates the tracking of desired path. We can see after exposing disturbance, the rejection of it is not well, and control cannot reject disturbance very well. But, figure 5 (b) shows the rejection of disturbance and tracking for robot with unknown parameters are well.



(a)



(b)

Figure 5. The path of robot angle with MRAC with disturbance: a) robot with known dynamic and kinetic parameters, b) robot with unknown dynamic and kinetic parameters

In order to compare the performance robot with known and unknown parameters with and without disturbance, sum mean value square error criterion is used.

The table 1, shows the comparison transient response between with known and unknown parameters with and without disturbance and the table 2, demonstrates these comparisons for path response.

Table 1. The mean value square criterion with MRAC with disturbance for control of transient response of robot

Robot with unknown parameters and with disturbance	Robot with known parameters and with disturbance	Robot with unknown parameters and without disturbance	Robot with known parameter and without disturbance	
2.06	3.75	1.81	4.42	Mean Value Theorem

Table 2. The mean value square criterion with MRAC with disturbance for control of path of robot

Robot with unknown parameters and with disturbance	Robot with known parameters and with disturbance	Robot with unknown parameters and without disturbance	Robot with known parameters and without disturbance	
1.34	3.26	1.63	4.79	Mean Value Theorem

Based on the above tables, we can conclude robot with known parameters has steady state error.

But robot with unknown parameters because of increasing unknown parameters can reduce the error and converge to desired path.

5. Conclusions

In this paper, designing the reference model based adaptive control for robot with two degrees of freedom is considered. In addition, the performance of robot with known and unknown dynamic and kinetics parameters in presence of disturbance is analyzed too. The simulation results and square mean value criterion show that robot with unknown parameters without disturbance, because has more freedom in examination of unknown parameters, has better tacking, and little steady state tracking error. By considering the disturbances in robot with known parameters the proposed method could not reject the disturbance very well, and has more error compared to track the desired path without disturbance. Moreover, when the parameters of robot are unknown in presence of disturbance, the disturbance rejection and tracking is also well.

REFERENCES

[1] B. Kehoe, S. Patil, P. Abbeel and K. Goldberg, "A Survey of Research on Cloud Robotics and Automation", IEEE Transactions on Automation Science and Engineering, vol. 12, No. 2, pp. 398- 409, (2015).

[2] M. Galicki," Finite- Time Trajectory Tracking Control in a Task Space of Robotic Manipulator" International Journal of automatic, Vol. 67, pp. 165.170, (2016).

[3] M. Mirzadeh, Gh. Ahrami, M. haghighi and A. Darveshi, "Intelligent Model- Reference Method to Control of Industrial Robot Arm", International Journal of u- and e-Service, Science and Technology, Vol. 8, No. 2, pp. 71- 90, (2015).

[4] P. Y. Huang, "Study of Optimal Path Planning and motion Control of a Delta Robot Manipulator", IEEE Transactions on Industrial Electronics, Vol. 49, No.1, pp. 224- 232, (2015).

[5] X. Wang and J. Zhao, "Switched adaptive Tracking Control of Robot Manipulators with Friction and Changing Loads", International Journal of Systems Science, Vol. 46, No. 6, pp. 955- 965, (2015).

[6] D. Zhao, Sh. Li and Q. Zhu, "Adaptive Synchronised Tracking Control for Multiple Robotic Manipulators with Uncertain Kinematics and Dynamics", International Journal of Systems Science, Vol. 47, No. 4, pp. 791- 804, (2016).

[7] M. R. Soltanpour and S. E. Shafiei, "Robust Adaptive Control of Manipulators in the Task Space By Dynamical Patitioning Approach", Internationa Journal of Electronika Ir Electrotechnika, Vol. 101, No.5 , pp. 73-78, (2010).

[8] M. Rahmani, A. Ghanbari and M. M. Ettefagh, "Robust Adaptive Control of bio- Inspired Rbot Manipulator Using Bat Algorithm", International Journal of Expert Systems with Applications, Vol. 56, pp. 164- 176, (2016).

[9] R. H. Mohammed, F. Bendary and K. Elserafi, "Trajectory Tracking Control for Robot Manipulator Using Fractional Order- Fuzzy- PID Controller", International Journal of Computer Applications, Vol.134, No.15 pp. 22-30, (2016).

[10] R. Sharma, P. Guar and A. P. Mittal, "Performance Analysis of Two- degree of Freedom Fractional Order PID Controllers for Robotics Manipulator with Payload", International Journal of ISA Transactions, Vol. 58, pp. 279-291, (2015).

[11] C. B. Kadu, S. B. Bhusal and S. B. Lukare, "Autotuning of the Controller for Robot Arm and Magnet Levitation Plant", International Journal of Research in Engineering and Technology, Vol. 4, No.1, pp. 186-193, (2015).

[12] H. T. Le, S. R. Lee and Gh. Y. Lee, "Integration Model Reference Adaptive Control and Exact Linearization with Disturbance Rejection for Control of Robot Manipulators", International Journal of Innovative Computing, Information and Control, Vol.7, No.6, pp. 3255- 3267, (2011).

[13] Ch. Ch. Cheah, M. Hirano, S. Kawamura and S. Arimoto, "Approximate Jacobian Control for Robots with Uncertain Kinematics and Dynamics", IEEE Transaction on Robotics and Automation, Vol. 19, No.4, pp. 692- 702, (2003).

[14] R. M. Murray, Z. Li and S. Sh. Sastry, "A Mathematical Introduction to Robotic Manipulation", California, CRC Press, (1994).

[15] H. Wang." Take-space synchronization of networked robotic systems with uncertain kinematics and dynamics", IEEE Transactions on Automatic Control, Vol. 58, No. 12, pp. 3169-3174, (Dec. 2013).

[16] J.-J. E. Slotine and W. Li, "On the adaptive control of robot manipulators," The International Journal of Robotics Research, vol. 6, no. 3, pp. 49–59, (Sep. 1987).

[17] H. Chae, An. Christopher, G. Atkeson and J. Hollerbach, "Model- Based Control of a Robot Manipulator", Cambridge, MA. MIT Press, (1988).

[18] K. S. Narendra and A. M. Annaswamy, "Stable Adaptive Systems," Prentice-Hall, (2012).

[19] Andani, Majid Taheri, and Zahra Ramezani. "Robust Control of a Spherical Mobile Robot." (2017).