Design Error-based Linear Model-free Evaluation Performance Computed Torque Controller

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Abstract

Design a nonlinear controller for second order nonlinear uncertain dynamical systems is one of the most important challenging works. This research focuses on the design, implementation and analysis of a model-free linear error-based tuning computed torque controller for highly nonlinear dynamic second order system, in presence of uncertainties. In order to provide high performance nonlinear methodology, computed torque controller is selected. Pure computed torque controller can be used to control of partly known nonlinear dynamic parameters of nonlinear systems. Conversely, pure computed torque controller is used in many applications; it has an important drawback namely; nonlinear equivalent dynamic formulation in uncertain dynamic parameter. In order to solve the uncertain nonlinear dynamic parameters, implement easily and avoid mathematical model base controller, model-free performance/error-based linear methodology with three inputs and one output is applied to pure computed torque controller. The results demonstrate that the error-based linear tuning computed torque controller is a model-based controllers which works well in certain and uncertain system. Pure computed torque controller has difficulty in handling unstructured model uncertainties. To solve this problem applied linear model-free error -based tuning method to computed torque controller for adjusting the linear inner loop gain (K). Since the linear inner loop gain (K) is adjusted by linear error-based tuning method, it is linear and continuous. In this research new K is obtained by the previous K multiple gain updating factor (α) which is a coefficient varies between half to two.

Keywords: Computed Torque Controller, Linear on-line Tuning Method, Gain Updating Factor, linear Inner loop Gain, Error-based Tuning Method.

1. INTRODUCTION, BACKGROUND and MOTIVATION

Controller is a device which can sense information from linear or nonlinear system (e.g., robot manipulator) to improve the systems performance [1-3]. The main targets in designing control systems are stability, good disturbance rejection, and small tracking error[4-5]. Several industrial robot manipulators are controlled by linear methodologies (e.g., Proportional-Derivative (PD) controller, Proportional- Integral (PI) controller or Proportional- Integral-Derivative (PID) controller), but when robot manipulator works with various payloads and have uncertainty in dynamic models this technique has limitations. From the control point of view, uncertainty is divided into two main groups: uncertainty in unstructured inputs (e.g., noise, disturbance) and uncertainty in structure dynamics (e.g., payload, parameter variations). In some applications robot manipulators are used in an unknown and unstructured environment, therefore strong mathematical tools used in new control methodologies to design nonlinear robust controller with an acceptable performance (e.g., minimum error, good trajectory, disturbance rejection). Computed torque controller is an influential nonlinear controller to certain and partly uncertain systems which it is based on system's dynamic model [6-20].

Computed torque controller (CTC) is a powerful nonlinear controller which it widely used in control of robot manipulator. It is based on feedback linearization and computes the required arm torques using the nonlinear feedback control law. This controller works very well when all dynamic and physical parameters are known but when the robot manipulator has variation in dynamic parameters, in this situation the controller has no acceptable performance[14]. In practice, most of physical systems (e.g., robot manipulators) parameters are unknown or time variant, therefore, computed torque like controller used to compensate dynamic equation of robot manipulator[1, 6]. Research on computed torque controller is significantly growing on robot manipulator application which has been reported in [1, 6, 15-16]. Vivas and Mosquera [15]have proposed a predictive functional controller and compare to computed torque controller for tracking response in uncertain environment. However both controllers have been used in feedback linearization, but predictive strategy gives better result as a performance. A computed torque control with non parametric regression models have been presented for a robot arm[16]. This controller also has been problem in uncertain dynamic models. Based on [1, 6]and [15-16] computed torque controller is a significant nonlinear controller to certain systems which it is based on feedback linearization and computes the required arm torques using the nonlinear feedback control law. When all dynamic and physical parameters are known, computed torque controller works fantastically; practically a large amount of systems have uncertainties, therefore sliding mode controller is one of the best case to solve this challenge.

In various dynamic parameters systems that need to be training on-line adaptive control methodology is used. Adaptive control methodology can be classified into two main groups, namely, traditional adaptive method and fuzzy adaptive method [21-75]. Fuzzy adaptive method is used in systems which want to training parameters by expert knowledge. Traditional adaptive method is used in systems which some dynamic parameters are known. In this research in order to solve disturbance rejection and uncertainty dynamic parameter, error-based linear adaptive method is applied to computed torque controller. Hsu et al. [54] have presented traditional adaptive methods which can update fuzzy rules to compensate nonlinear parameters and guarantee the stability. Hsueh et al. [43] have presented traditional self tuning method which can resolve the controller problem.

For nonlinear dynamic systems with various parameters, adaptive control technique can train the dynamic parameter to have an acceptable controller performance. Calculate several scale factors are common challenge in pure computed torque controller, as a result it is used to adjust and tune coefficient.

This paper is organized as follows:
In section 2, detail of classical computed torque controller is presented. In section 3, design error-based linear tuning method is presented and applied to computed torque controller; this method

is used to reduce the error performance and estimation the equivalent part. In section 4, simulation result is presented and finally in section 5, the conclusion is presented.

2. CASE STUDY and COMPUTED TORQUE CONTROLLER FORMULATION

Case study (Robot manipulator dynamic formulation): The equation of an *n-DOF* robot manipulator governed by the following equation [1, 3, 15-29]:

$$M(q)\ddot{q} + N(q,\dot{q}) = \tau \quad (1)$$

Where τ is actuation torque, M (q) is a symmetric and positive define inertia matrix, $N(q,\dot{q})$ is the vector of nonlinearity term. This robot manipulator dynamic equation can also be written in a following form:

$$\tau = M(q)\ddot{q} + B(q)[\dot{q}\,\dot{q}] + C(q)[\dot{q}]^2 + G(q) \quad (2)$$

Where B(q) is the matrix of coriolios torques, C(q) is the matrix of centrifugal torques, and G(q) is the vector of gravity force. The dynamic terms in equation (2) are only manipulator position. This is a decoupled system with simple second order linear differential dynamics. In other words, the component $\ddot{q}$ influences, with a double integrator relationship, only the joint variableq_i, independently of the motion of the other joints. Therefore, the angular acceleration is found as to be [3, 10-29]:

$$\ddot{q} = M^{-1}(q).\{\tau - N(q,\dot{q})\} \quad (3)$$

Computed Torque Controller: The central idea of Computed torque controller (CTC) is feedback linearization so, originally this algorithm is called feedback linearization controller. It has assumed that the desired motion trajectory for the manipulator $q_d(t)$, as determined, by a path planner. Defines the tracking error as:

$$e(t) = q_d(t) - q_a(t) \quad (4)$$

Where e(t) is error of the plant, $q_d(t)$ is desired input variable, that in our system is desired displacement, $q_a(t)$ is actual displacement. If an alternative linear state-space equation in the form $\dot{x} = Ax + BU$ can be defined as

$$\dot{x} = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ I \end{bmatrix} U \quad (5)$$

With $U = -M^{-1}(q).N(q,\dot{q}) + M^{-1}(q).\tau$ and this is known as the Brunousky canonical form. By equation (4) and (5) the Brunousky canonical form can be written in terms of the state $x = [e^T\ \dot{e}^T]^T$ as [1]:

$$\frac{d}{dt}\begin{bmatrix} e \\ \dot{e} \end{bmatrix} = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix} . \begin{bmatrix} e \\ \dot{e} \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix} U \quad (6)$$

With

$$U = \ddot{q}_d + M^{-1}(q).\{N(q.\dot{q}) - \tau\} \quad (7)$$

Then compute the required arm torques using inverse of equation (7), is;

$$\tau = M(q)(\ddot{q}_d - U) + N(\dot{q},q) \quad (8)$$

This is a nonlinear feedback control law that guarantees tracking of desired trajectory. Selecting proportional-plus-derivative (PD) feedback for U(t) results in the PD-computed torque controller [6];

$$\tau = M(q)\left(\ddot{q}_d + K_v\dot{e} + K_p e\right) + N(q,\dot{q}) \quad (9)$$

and the resulting linear error dynamics are

$$\left(\ddot{q}_d + K_v\dot{e} + K_p e\right) = 0 \quad (10)$$

According to the linear system theory, convergence of the tracking error to zero is guaranteed [6]. Where K_p and K_v are the controller gains. The result schemes is shown in Figure 1, in which two feedback loops, namely, inner loop and outer loop, which an inner loop is a compensate loop and an outer loop is a tracking error loop.

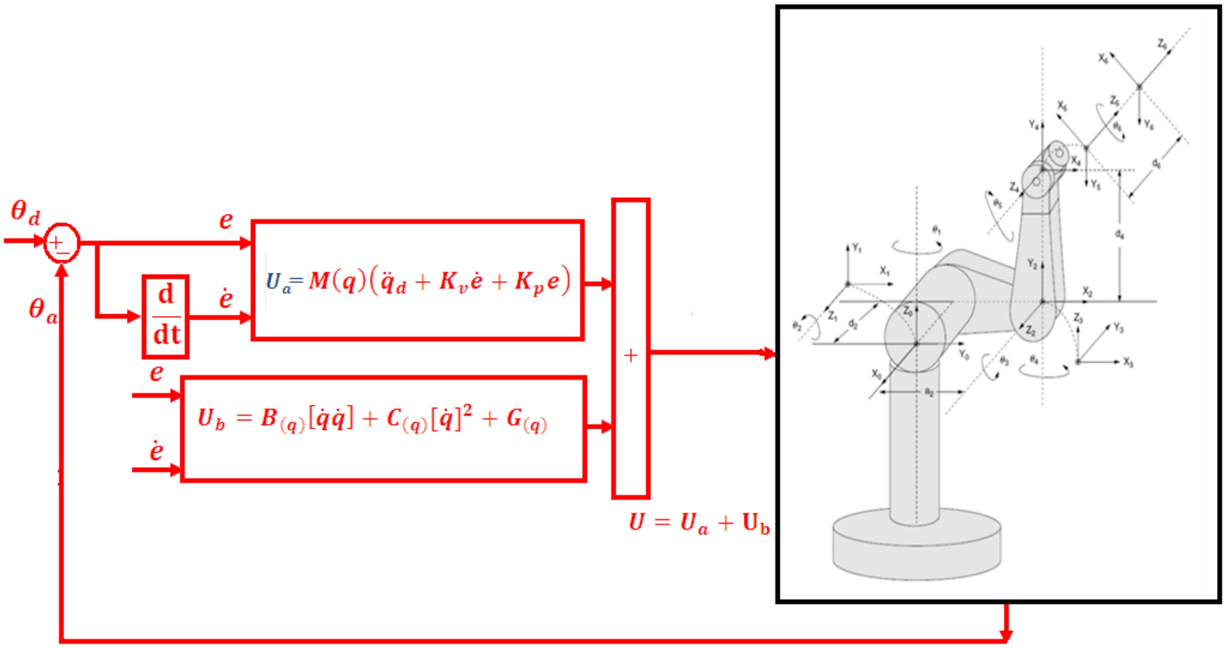

FIGURE 1: Block diagram of PD-computed torque controller (PD-CTC)

The application of proportional-plus-derivative (PD) computed torque controller to control of 6 DOF robot manipulator introduced in this part. Suppose that in (9) the nonlinearity term defined by the following term

$$N(q,\dot{q}) = B(q)\dot{q}\dot{q} + C(q)\dot{q}^2 + g(q) = \begin{bmatrix} b_{112}\dot{q}_1\dot{q}_2 + b_{113}\dot{q}_1\dot{q}_3 + 0 + b_{123}\dot{q}_2\dot{q}_3 \\ 0 + b_{223}\dot{q}_2\dot{q}_3 + 0 + 0 \\ 0 \\ b_{412}\dot{q}_1\dot{q}_2 + b_{413}\dot{q}_1\dot{q}_3 + 0 + 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} C_{12}\dot{q}_2{}^2 + C_{13}\dot{q}_3{}^2 \\ C_{21}\dot{q}_1{}^2 + C_{23}\dot{q}_3{}^2 \\ C_{31}\dot{q}_1{}^2 + C_{32}\dot{q}_2{}^2 \\ 0 \\ C_{51}\dot{q}_1{}^2 + C_{52}\dot{q}_2{}^2 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \\ g_5 \\ 0 \end{bmatrix} \tag{11}$$

Therefore the equation of PD-CTC for control of robot manipulator is written as the equation of (12);

$$\begin{bmatrix} \widehat{\tau_1} \\ \widehat{\tau_2} \\ \widehat{\tau_3} \\ \widehat{\tau_4} \\ \widehat{\tau_5} \\ \widehat{\tau_6} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix} \begin{bmatrix} \ddot{q}_{d1} + K_{v1}\dot{e}_1 + K_{p1}e_1 \\ \ddot{q}_{d2} + K_{v2}\dot{e}_2 + K_{p2}e_2 \\ \ddot{q}_{d3} + K_{v3}\dot{e}_3 + K_{p3}e_3 \\ \ddot{q}_{d4} + K_{v4}\dot{e}_4 + K_{p4}e_4 \\ \ddot{q}_{d5} + K_{v5}\dot{e}_5 + K_{p5}e_5 \\ \ddot{q}_{d6} + K_{v6}\dot{e}_6 + K_{p6}e_6 \end{bmatrix} + \begin{bmatrix} b_{112}\dot{q}_1\dot{q}_2 + b_{113}\dot{q}_1\dot{q}_3 + 0 + b_{123}\dot{q}_2\dot{q}_3 \\ 0 + b_{223}\dot{q}_2\dot{q}_3 + 0 + 0 \\ 0 \\ b_{412}\dot{q}_1\dot{q}_2 + b_{413}\dot{q}_1\dot{q}_3 + 0 + 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} C_{12}\dot{q}_2{}^2 + C_{13}\dot{q}_3{}^2 \\ C_{21}\dot{q}_1{}^2 + C_{23}\dot{q}_3{}^2 \\ C_{31}\dot{q}_1{}^2 + C_{32}\dot{q}_2{}^2 \\ 0 \\ C_{51}\dot{q}_1{}^2 + C_{52}\dot{q}_2{}^2 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \\ g_5 \\ 0 \end{bmatrix} \tag{12}$$

The controller based on a formulation (12) is related to robot dynamics therefore it has problems in uncertain conditions.

3. METHODOLOGY: ERROR-BASED LINEAR MODEL-FREE TUNING COMPUTED TORQUE CONTROLLER

Computed torque controller has difficulty in handling unstructured model uncertainties. It is possible to solve this problem by combining computed torque controller and linear error-based tuning method which this method can helps to eliminate the error and improves the system's tracking performance by online tuning method. In this research the nonlinear equivalent dynamic (equivalent part) formulation problem in uncertain system is solved by using on-line linear error-based tuning theorem. In this method linear error-based theorem is applied to computed torque controller to adjust the linear inner loop gain. Computed torque controller has difficulty in handling unstructured model uncertainties and this controller's performance is sensitive to linear inner loop gain. It is possible to solve above challenge by combining linear error-based tuning method and computed torque controller which this methodology can help to improve system's tracking performance by on-line tuning (linear error-based tuning) method. Based on above discussion, compute the best value of linear inner loop gain has played important role to improve system's tracking performance especially when the system parameters are unknown or uncertain. This problem is solved by tuning the linear inner loop gain ($\boldsymbol{K}$) of the computed torque controller continuously in real-time. In this methodology, the system's performance is improved with respect to the pure computed torque controller. Figure 2 shows the linear error-based tuning computed torque controller.

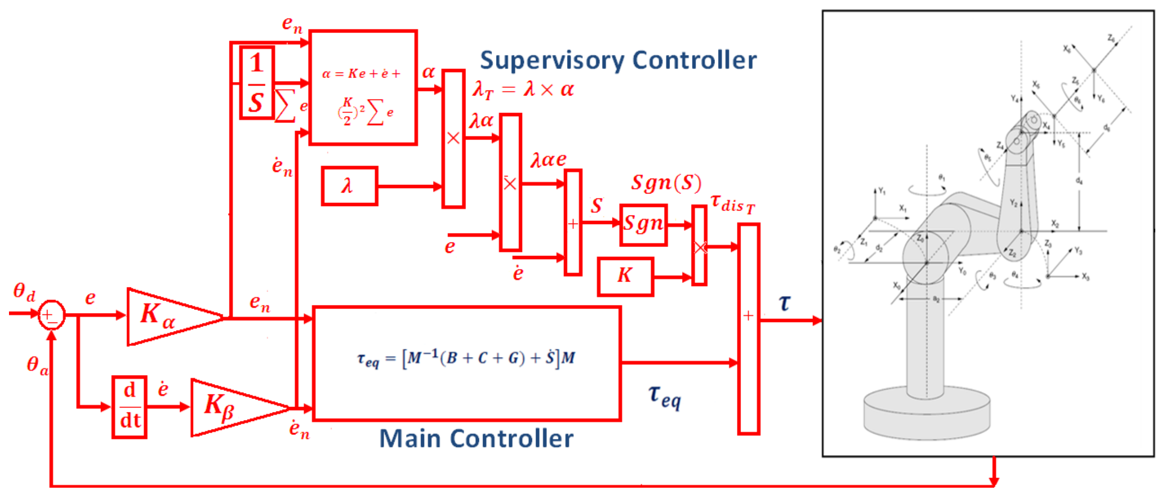

FIGURE 2: Block diagram of a linear error-based computed torque controller: applied to robot arm

$$\hat{f}(x|\lambda) = \lambda^T \alpha \tag{13}$$

If minimum error ($\boldsymbol{\lambda}^*$) is defined by;

$$\lambda^* = arg\ min\ [(Sup|\hat{f}(x|\lambda) - f(x))] \tag{14}$$

Where λ^T is adjusted by an adaption law and this law is designed to minimize the error's parameters of $\boldsymbol{\lambda} - \boldsymbol{\lambda}^*$. adaption law in linear error-based tuning computed torque controller is used to adjust the linear inner loop gain. Linear error-based tuning part is a supervisory controller based on the following formulation methodology. This controller has three inputs namely; error (e), change of error ($\dot{e}$) and the integral of error ($\sum e$) and an output namely; gain updating factor(α). As a summary design a linear error-based tuning is based on the following formulation:

$$\alpha = K.e + \dot{e} + \frac{(K)^2}{2}\sum e \qquad (15)$$

$$K_{on-line} = \alpha.\lambda e + \dot{e} \Rightarrow K_{on-line} = (K.e + \dot{e} + \frac{(K)^2}{2}\sum e)\lambda e + \dot{e}$$

$$\lambda_{Tune} = \lambda.\alpha \Rightarrow \lambda_{Tune} = \lambda(K.e + \dot{e} + \frac{(K)^2}{2}\sum e)$$

Where (α) is gain updating factor, $(\sum e)$ is the integral of error, $(\dot{e})$ is change of error, (e) is error and K is a coefficient.

4 Simulation Results

Pure computed torque controller has difficulty in handling unstructured model uncertainties. It is possible to solve this problem by combining computed torque controller and linear error-based tuning in a single controller method. This method can improve the system's tracking performance by online tuning method. This method is based on resolve the on line linear inner loop gain as well as improve the output performance by tuning the linear inner loop coefficient. The linear inner loop gain $(\boldsymbol{K})$ of this controller is adjusted online depending on the last values of error (e), change of error $(\dot{e})$ and integral of error by gain updating factor (α).

Tracking performances: Based on (12) in computed torque controller; controller performance is depended on the linear inner loop gain updating factor (K). These two coefficients are computed by trial and error in CTC. The best possible coefficients in step CTC are; $K_p = K_v = K_i = 18$. In linear error-based tuning computed torque controller the linear inner loop gain is adjusted online depending on the last values of error (e), change of error $(\dot{e})$ and integral of error by gain updating factor (α). Figure 3 shows tracking performance in computed torque controller (CTC) and linear tuning computed torque controller (LTCTC) without disturbance for step trajectory.

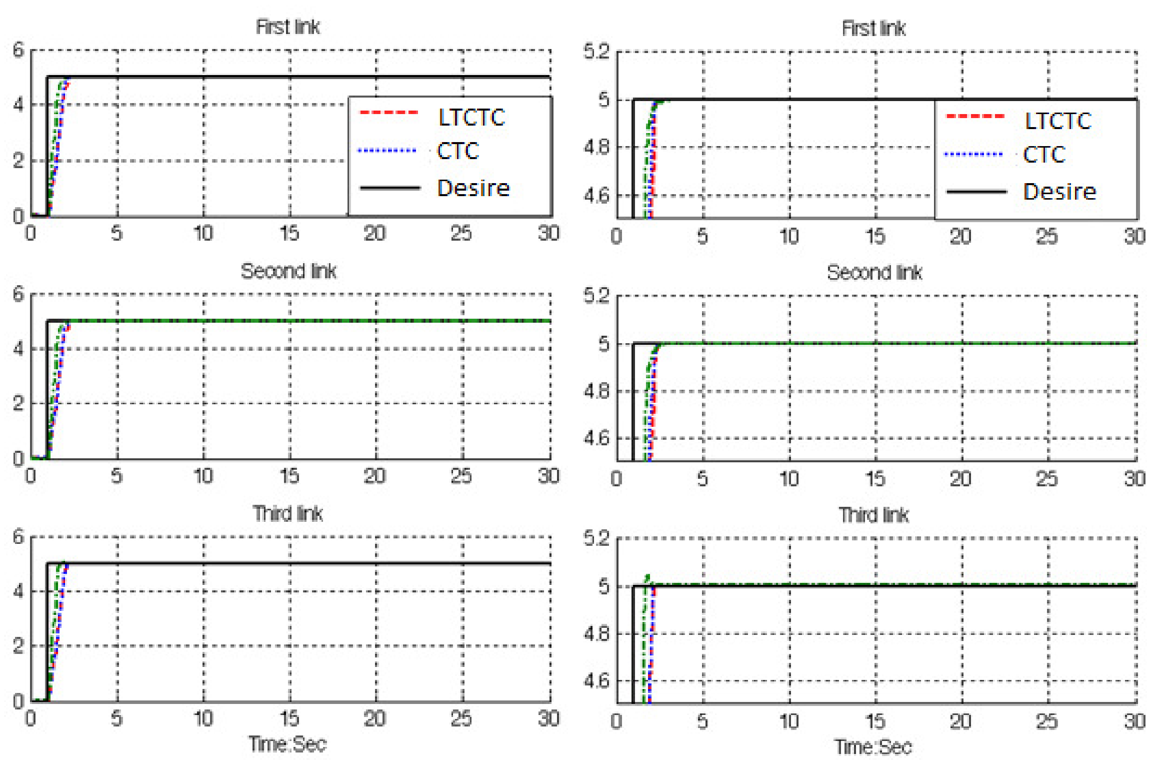

FIGURE 3: CTC, LTCTC and desired input for first, second and third link step trajectory performance without disturbance

Based on Figure 3 it is observed that, the overshoot in LTCTC is 0% and in CTC's is 1%, and rise time in LTCTC's is 0.6 seconds and in CTC's is 0.483 second. From the trajectory MATLAB simulation for LTCTC and CTC in certain system, it was seen that all of two controllers have acceptable performance.

Disturbance Rejection: Figures 4 to 6 show the power disturbance elimination in LTCTC and CTC with disturbance for step trajectory. The disturbance rejection is used to test the robustness comparisons of these two controllers for step trajectory. A band limited white noise with predefined of 10%, 20% and 40% the power of input signal value is applied to the step trajectory. It found fairly fluctuations in trajectory responses.

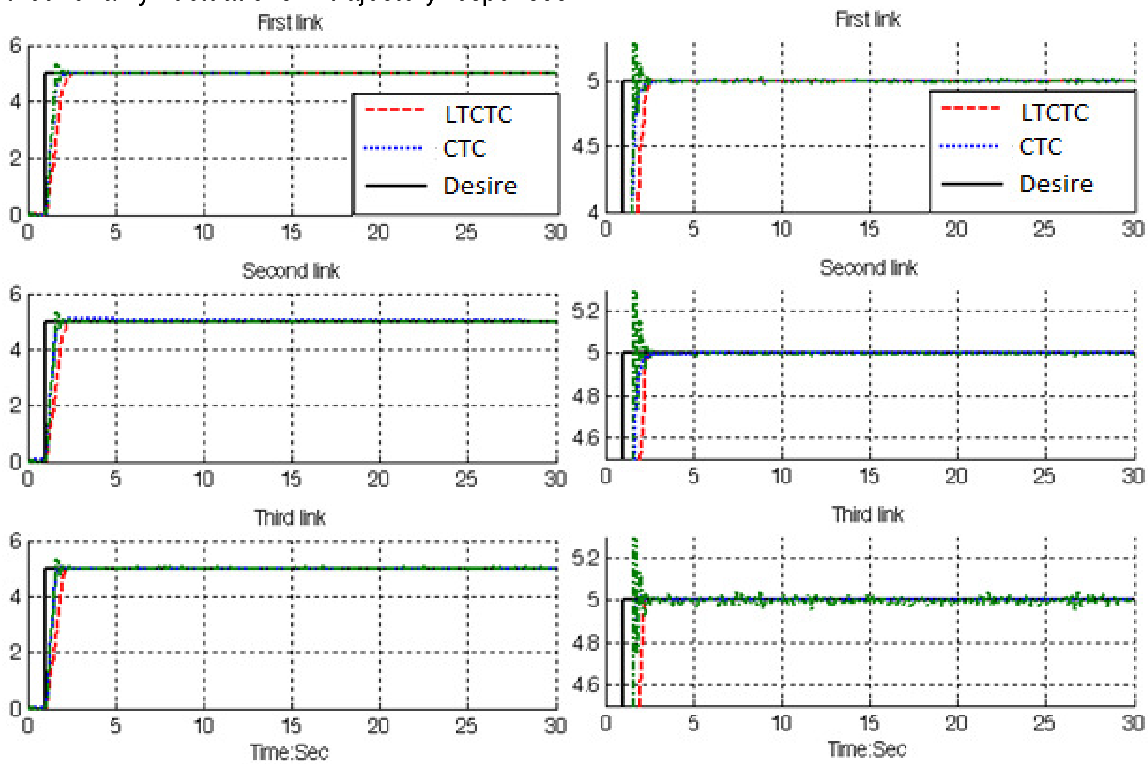

FIGURE 4: Desired input, LTCTC and CTC for first, second and third link trajectory with 10%external disturbance: step trajectory

Based on Figure 4; by comparing step response trajectory with 10% disturbance of relative to the input signal amplitude in LTCTC and CTC, LTCTC's overshoot about (0%) is lower than PD-CTC's (**1%**)**.** CTC's rise time **(0.5 seconds)** is lower than LTCTC's **(0.65 second).** Besides the Steady State and RMS error in LTCTC and CTC it is observed that, error performances in LTCTC **(Steady State error =1.08e-12 and RMS error=1.5e-12)** are bout lower than CTC's **(Steady State error=1.6e-6 and RMS error=1.9e-6)**.

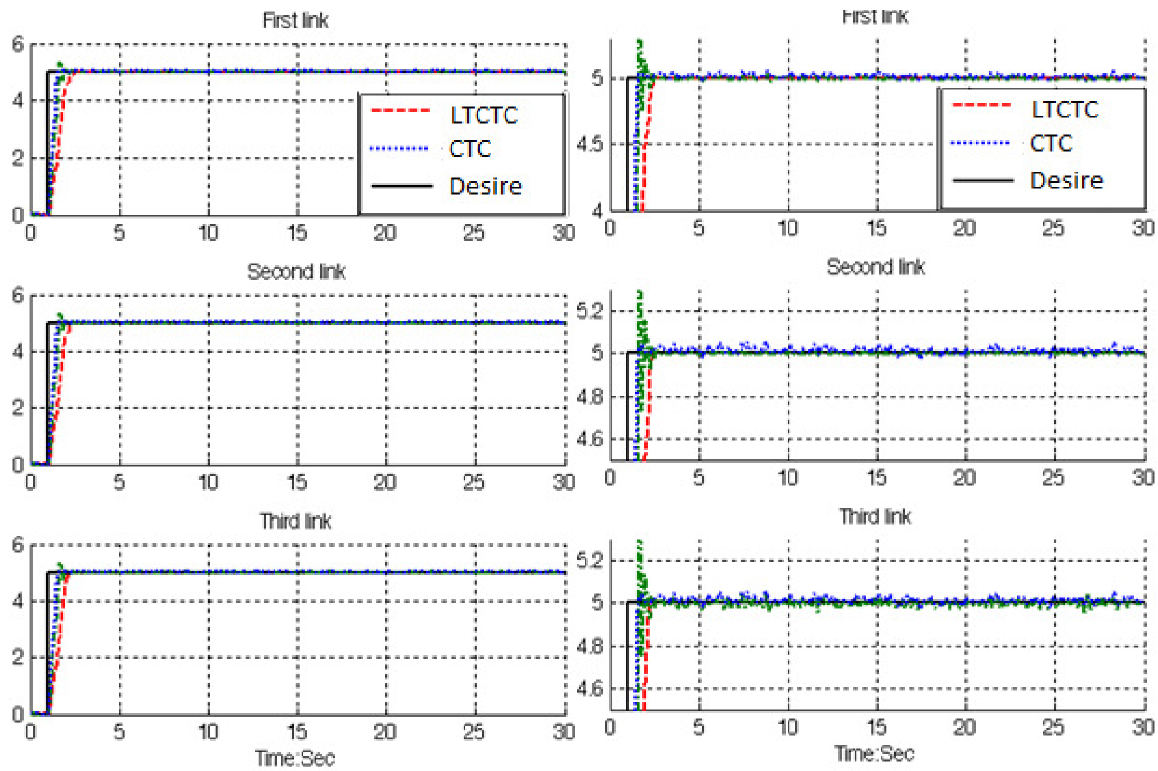

FIGURE 5: Desired input, LTCTC and CTC for first, second and third link trajectory with 20%external disturbance: step trajectory

Based on Figure 5; by comparing step response trajectory with 20% disturbance of relative to the input signal amplitude in LTCTC and CTC, LTCTC's overshoot about **(0%)** is lower than CTC's (**2.1%**)**.** CTC's rise time **(0.5 seconds)** is lower than LTCTC's **(0.66 second).** Besides the Steady State and RMS error in LTCTC and CTC it is observed that, error performances in LTCTC **(Steady State error =1.2e-12 and RMS error=1.8e-12)** are about lower than CTC's **(Steady State error=1.8e-5 and RMS error=2e-5)**. Based on Figure 5, it was seen that, LTCTC's performance is better than CTC because LTCTC can auto-tune the inner loop gain coefficient as the dynamic manipulator parameter's change and in presence of external disturbance whereas CTC cannot.

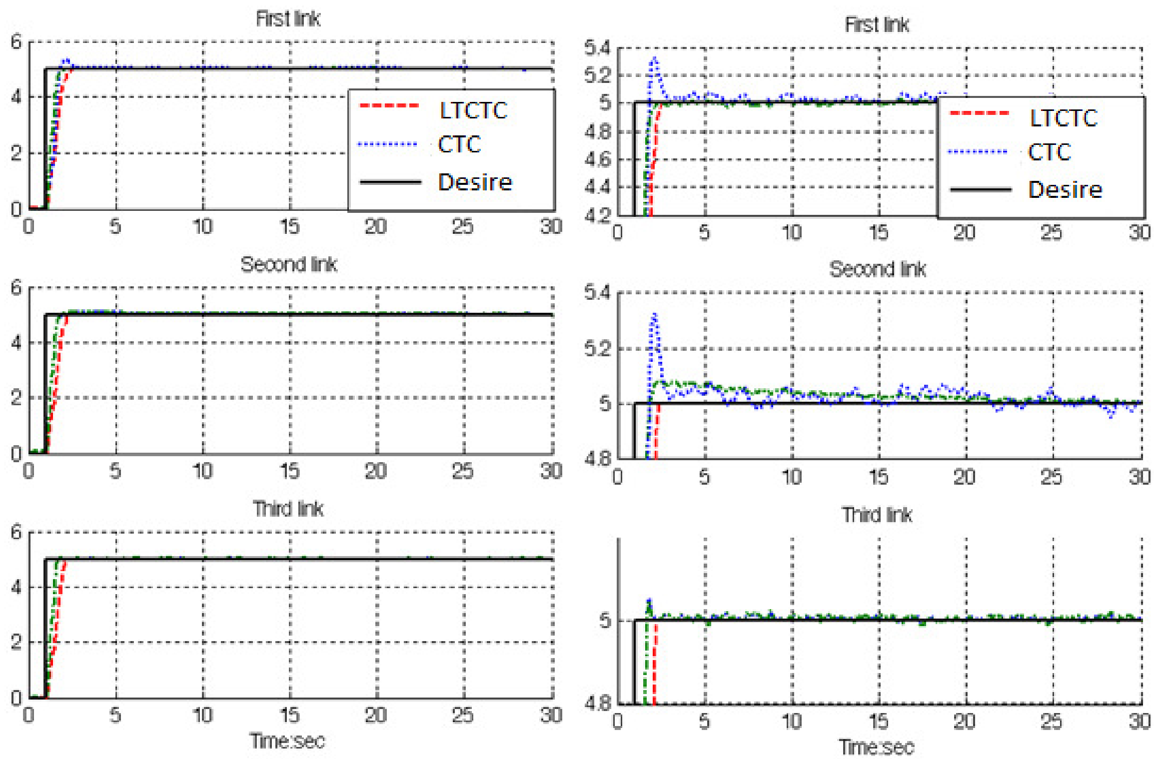

FIGURE 6: Desired input, LTCTC and CTC for first, second and third link trajectory with 40%external disturbance: step trajectory

Based on Figure 6; by comparing step response trajectory with 40% disturbance of relative to the input signal amplitude in LTCTC and CTC, LTCTC's overshoot about **(0%)** is lower than CTC (**8%**)**.** CTC's rise time **(0.5 seconds)** is lower than LTCTC's **(0.8 second).** Besides the Steady State and RMS error in LTCTC and CTC it is observed that, error performances in LTCTC **(Steady State error =1.3e-12 and RMS error=1.8e-12)** are about lower than CTC's **(Steady State error=10e-4 and RMS error=11e-4).** Based on Figure 6, CTC has moderately oscillation in trajectory response with regard to 40% of the input signal amplitude disturbance but LTCTC has stability in trajectory responses in presence of uncertainty and external disturbance. Based on Figure 6 in presence of 40% unstructured disturbance, LTCTC's is more robust than CTC because LTCTC can auto-tune the inner loop coefficient as the dynamic manipulator parameter's change and in presence of external disturbance whereas CTC cannot.

Steady state error: The error performance is used to test the disturbance effect comparisons of these controllers for step trajectory. All three joint's inputs are step function with the same step time (step time= 1 second), the same initial value (initial value=0) and the same final value (final value=5). LTCTC's rise time is about 0.6 second, and CTC's rise time is about 0.6 second which caused to create a needle wave in the range of 5 (amplitude=5) and the different width. In this system this time is transient time and this part of error introduced as a transient error. Besides the Steady State and RMS error in LTCTC and CTC it is observed that, error performances in LTCTC **(Steady State error =0.9e-12 and RMS error=1.1e-12)** are bout lower than CTC's **(Steady State error=1e-8 and RMS error=1.2e-6)**. The LTCTC gives significant steady state error performance when compared to CTC. When applied 40% disturbances in LTCTC the RMS error increased approximately 0.0164% (percent of increase the LTCTC RMS error=$\frac{(40\%\ disturbance\ RMS\ error}{no\ disturbanceRMS\ error} = \frac{1.8e-12}{1.1e-12} = 0.0164\%$), in CTC the RMS error increased approximately 9.17% (percent of increase the PD-SMC RMS error=$\frac{(40\%\ disturbance\ RMS\ error}{no\ disturbance\ RMS\ error} = \frac{11e-4}{1.2e-6} = 9.17\%$). In this part LTCTC and CTC have been comparatively evaluation through

MATLAB simulation, for PUMA robot manipulator control. It is observed that however LTCTC is dependent of nonlinear dynamic equation of PUMA 560 robot manipulator but it can guarantee the trajectory following in certain systems, structure uncertain systems and unstructured model uncertainties by online tuning method.

5. CONCLUSIONS

Refer to this research, a linear model-free error-based tuning computed torque controller (LTCTC) is proposed for robot manipulator. The first problem of the pure CTC was adjust the linear inner loop gain in certain and uncertain systems. this problem can be reduced in certain system by using trial and error methodology in computed torque control law. The simulation results exhibit that the CTC works well in certain system. The nonlinear equivalent dynamic problem in uncertain system is solved by using on-line tuning method. Pure CTC has difficulty in handling unstructured model uncertainties. It is possible to solve this problem by combining error-based linear methodology and computed torque controller. Since the linear inner loop gain (K) is adjusted by linear tuning method. The linear inner loop gain updating factor (α) of error-based tuning part can be changed with the changes in error and change of error and integral of error rate between half to two. linear inner loop gain is adapted on-line by linear inner loop gain updating factor. In pure CTC the linear inner loop gain is chosen by trial and error, which means pure CTC has to have a prior knowledge of the system uncertainty. If the knowledge is not available error performance is go up. In LTCTC the linear inner loop gain is updated on-line to compensate the system unstructured uncertainty. The simulation results exhibit that the LTCTC works well in various situations. Based on theoretical and simulation results, it is observed that LTCTC is a model-based stable control for robot manipulator. It is a good solution to reduce the error in structure and unstructured uncertainties.

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