A Robot Joint Model with Minimal Order Controller and State Observer

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***Abstract*— In this paper a novel control method and state observer are proposed for an autonomous humanoid robot joint model for fast tracking response and superior performance.**

The various movements of the robot for pre specified joint trajectories can be achieved using proposed controller. The controller is simple and is able to produce desirable results. The linearized robot joint model is controlled by a simpler order feedback control designed on the basis of quasi-linear feedback theory. Under this design, the pole of the lead-lag compensator depends on the gain of open loop system. A simulink model is developed to model single joint in the body. The proposed controller guarantees fast tracking of the desired trajectories, as well ensures the safety.

Since the plant model involves differentiation of a state variable to generate another, resulting in a reduction of signal to noise ratio, a state observer is designed for the feedback system to ensure maximum safety and improved performance. The simulations are done showing the validity of the scheme. Pole placement method is used to design the observer parameters. The application of proposed controller and state observer is illustrated by linear model.

***Index Terms*— Humanoid, robot joint system, state observer.**

I. INTRODUCTION

Robots are very powerful elements of today's industry. They are capable of performing many tasks and operations precisely and do not require common safety and comfort elements humans need. However it takes much effort and many resources to make a robot function properly.

Development of Robotic can be observed all over the world. Robots replace human work in many areas. They can work in offices, homes and in environments that are harmful to humans. To this purpose robots of a different kind are being built.

A main problem which is explicit for the implementation of new robot concepts is the intrinsic flexibility introduced into the robot joints. Thus, the success in the robotics fields is mainly dependent on the design and implementation of ample control strategies to provide fast control. This paper will address one of those problems: a joint control.

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A reduction gear unit such as harmonic drive gear is used to drive each joint of robot arm. Serious problems of vibratory behavior are being caused because of the elasticity of the driving systems including these reduction gear units [1], [2].

To generate the required velocities needed for a mobile robot to move to a waypoint, Cerebellar Model Articulated Controller or CMAC was used. Significant sensory delay was introduced that would cripple a traditional control system [3].CMAC implemented for control system on a 2 degree of freedom arm, actuated by three opposing sets of muscles. The CMAC was responsible for the co-ordination of these three actuators to control the two joints. When the CMAC did not bring the arm to the required position, an additional external CMAC was engaged that produced short sharp bursts of motor activity until the target was reached [4].

For assisting a conventional PI controller with trajectory tracking, Trajectory Error Learning (TEL) based on a CMAC neural network is used [5].

The Integral diverse and singular perturbation techniques solve the control problem by a two stage approach [6], [7]. They propose a fast joint torque control loop, corresponding to the fast part of the manipulator dynamics and a slower outer control loop corresponding to the rigid body dynamics of the robot. These control strategies use the assumption of a weak elasticity of the joints. In the case of the DLR light-weight robot this is just marginally satisfied. [8] showed that the difficult part of this method is the implementation of the fast joint torque controller. Under conditions of considerable elasticity and noisy torque and torque derivative signals, the bandwidth of the resulting torque controller limits the overall bandwidth of the system.

In [9] Adaptive Neural Network control method was used to control the position of the joint.

For robot joint system, a fuzzy model-based controller was designed and implemented using IMA frame work [10]. The output response was improved but the researcher has to follow number of fuzzy rules.

For a laboratory scale robot arm with joint flexibility Iterative learning control (ILC) was applied. The ILC algorithm based on an estimate of the arm angle, where the estimate is formed using measurements of the motor angle and the arm angular acceleration were used. The design of the ILC algorithm was based on a model obtained from system identification [11].

Anthropomorphic biped robot is proposed by a British

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company "Shadow". In their project they use artificial McKibben muscles for actuating robot joints. These muscles are characterized by variable stiffness [12] which makes smooth and dynamic movement possible. Imperfection of this actuator is the nonlinear force characteristic, which makes control more complex in comparison to electric motors.

The PI compensator can be used to eliminate steady state error by adding a pole at the origin and thus increasing the system type. In our joint compensation scheme (using Quasi-linear) the open loop remains linear in the s (and t) variable but its poles depend non-linearly on the gain k; its performance is superior to that of the PI controller. Compared to other controllers (linear), this one is efficient and easy to implement even for many DOF. Whereas the plant model involves differentiation of a state variable to generate another, the problem of signal to noise ratio can be solved by designing state observer.

The paper organization includes modeling and control of single joint system in section II. The controller design and observer design is presented in section III. Block diagram of shoulder joint model for simulations, and some computer simulations of the scheme are given in section IV. Conclusions are given in section V.

II. MODELING AND CONTROL OF SINGLE JOINT

This section focuses on the mechanism and control of most important part of robot manipulator called a joint. Manipulator (this is the main body of the robot) consists of nearly rigid links, which are connected by joints that allow relative motion of neighboring links. Robots may have different types of joints, such as linear, rotary, sliding, or spherical. Although spherical joints are common in many systems, since they posses multiple degrees of freedom, and thus, are difficult to control. Most robots have either a linear (prismatic) joint or a rotary (revolute) joint. Prismatic joints are linear; there is no rotation involved. They are either hydraulic or pneumatic cylinders, or they are linear electric actuators. These joints are used in gantry, cylindrical, or similar joint configurations. Revolute joints are rotary, and although hydraulic and pneumatic rotary joints are common, most rotary joints are electrically driven, either by stepper motors or, more commonly, by servomotors.

In robot configuration, prismatic joints are denoted by P, revolute joints are denoted by R, and spherical joints are denoted by S. For example, a robot with three prismatic and three revolute joints is specified by 3P3R. In open loop robot system if all joint variables are set to particular values, there is no guarantee that the hand will be at the given location. This is because if there is any deflection in any joint or link, it will change the location of all subsequent links without feedback. A joint model is developed to be controlled with a suitable feedback controller capable of fast tracking response ensuring safety.

A. Modeling

Commonly the direct current (DC) torque motor is found for actuator of robots. Torque generated when current passes through the windings of rotor can be expressed as

$$F = qV * B \tag{1}$$

Where charge q, moving velocity V through a magnetic field B, experiences a force F. Motor torque constant, is given by

$$\tau_m = k_m i_a \tag{2}$$

Where i_a armature is current, k_m is scale factor and τ_m is output torque.

When a motor is rotating, it acts as a generator; other motor constant is back emf constant is given by

$$v = k_m \dot{\theta}_m \tag{3}$$

Rotor/ armature equation can be written as

$$l_a \dot{i}_a + r_a i_a = v_a - k_e \dot{\theta}_m \tag{4}$$

The inductance of motor can be neglected. Along with this assumption we can essentially command torque directly. Or we assume that the actuator acts as a pure torque source that we can command directly.

Fig. 1 shows the mechanical model of the rotor of a DC torque motor connected through a gear reduction to an inertia load. The gear ratio (η) causes an increase in the torque at load and a reduction in the speed of the load, given by

$$\tau = \eta \tau_m \ ,$$

$$\dot{\theta} = \frac{1}{\eta} \dot{\theta}_m \tag{5}$$

Where $\eta > 1$. In terms of torque at the rotor, torque balance equation yields

$$\tau_m = I_m \ddot{\theta}_m + b_m \dot{\theta}_m + \left(\frac{1}{\eta}\right)(I \ddot{\theta} + b \dot{\theta}) \tag{6}$$

Where I_m and I are the inertias of the motor rotor and of the load respectively, and b_m, b are viscous friction coefficients for the rotor and load bearings respectively.

By using (5), we can write (6) in terms of motor variables as

$$\tau_m = \left(I_m + \frac{I}{\eta^2}\right)\ddot{\theta}_m + \left(b_m + \frac{b}{\eta^2}\right)\dot{\theta}_m \tag{7}$$

Or in terms of load variables as

$$\tau = (I + \eta^2 I_m)\ddot{\theta} + (b + \eta^2 b_m)\dot{\theta} \tag{8}$$

The term $I + \eta^2 I_m$ may be called the effective inertia, and $b + \eta^2 b_m$ the effective damping.

Transfer function can be written:

$$\frac{\theta(s)}{\tau(s)} = \frac{1}{((I + \eta^2 I_m)s + (b + \eta^2 b_m))s} \tag{9}$$

B. Control:

The following three major assumptions are made to control single joint.

1) The motor inductance can be neglected

High gearing is taken in to account to model the effective inertia as constant equal to $I_{\max} + \eta I_m$.

2) Structural flexibilities are neglected.

Functional block diagram of Joint control system for robot is shown in fig.2

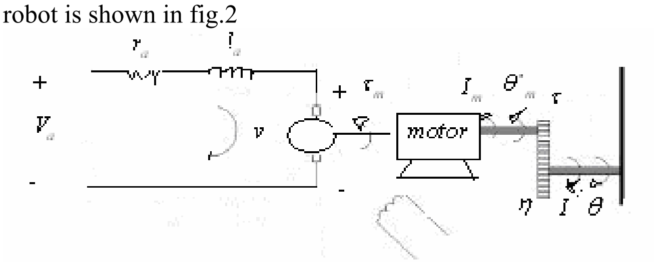

Fig.1 Model of a DC torque motor connected through gearing to an inertia load

Each joint is controlled by local controllers that its motor is connected to, and is instrumented with an encoder to obtain the current joint position. In order to command torques to the DC torque motors, the microprocessor can be interfaced to a digital-to-analog converter (D/A) so that motor currents commanded to the current driver circuits. The current flowing through the motor is controlled in analog circuitry by adjusting the voltage across the armature as needed to maintain the desired armature current [13].

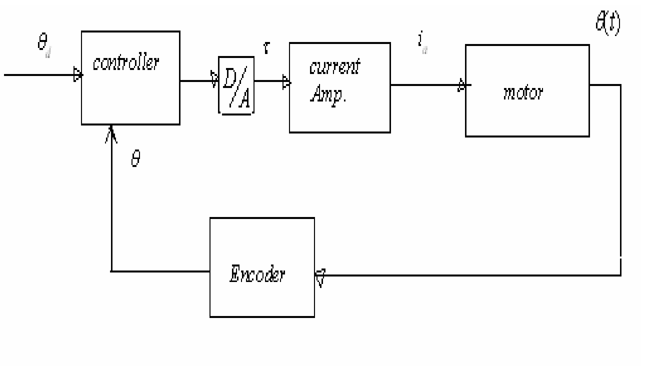

Fig.2 Block diagram of the robot joint-control system

III. CONTROLLER AND OBSERVER DESIGN

A. Controller objectives

Different approaches for controller synthesis exist in the literature, each having its own pros and cons. In the problem of robot joint, our foremost concern is to achieve a fast operation of the nominal system, within the limitations of performance.

In the quasi-linear feedback system, some of the open loop poles may depend on the open loop gain, such that the output of the system can track arbitrary fast its input. Consider a Feedback Structure in which KL(s) is the loop transmission, where K is a positive gain. Usually KL(s) contains the plant, independent of K, and the (feed back) compensator which is the one depending on K. The main purpose of this feedback is to remove the demanding constraint imposed on the performance of closed loop by excess in number of poles over zeros of the open loop KL(s).After feedback linearization of system, the transfer function of the resulting system has two integrators and one or two stable poles in excess to zeros. The output of a single-input single-output linear feedback system with more than one pole in excess over the zeros in the loop transmission cannot track arbitrarily fast its input [14]. One example is presented here which motivates employing such a controller and hence illustrate these results [14]. It also shows that this good performance can be obtained with a reduced control effort. The general structure of the quasi-linear compensator is explained as follows. Consider a plant described by

$$P(s) = 1/s^2 \tag{10}$$

$$G_c(s) = K\frac{s+1}{s+2} \tag{11}$$

The value of the gain K is tuned until a good performance of the control is achieved, so we raise the gain K > 0 to increase the performance of the closed loop and use the lead-lag compensation for ensuring some phase margin. At the value of gain K =1000, a quite slow and highly oscillatory response to a step input is obtained as shown in Fig. 3.This is because of the fact that raising the value of K with a compensator as in (11), the frequency component of eigen values of the closed loop system remain unchanged whereas the imaginary part change drastically. As a rough measure the imaginary part is scaled by a factor of 3 for every rise in scaling of K by 10. So the oscillations in response grow larger with increasing K in this fashion. However, with a slightly different compensator,

$$G_k(s) = K\frac{(s+a)}{(s+2K^{0.6})} \tag{12}$$

Again choosing a=1 and with K=1000, as in (12), the results are completely different as shown in Fig. 4. This great improvement of performance was obtained without any change in the order of compensation (which is already minimal), but by letting the pole of the compensator depend on the gain K itself: the exponent of K was f = 0 in Fig. 3 and f= 0.6 in Fig.4. The first compensator is a linear one and the compensator for the latter case is termed as `quasi-linear'. Consider the plant transfer function P(s) =1/s (plant with one integrator) and the excess of the number of poles over zeros is d=1(no. of poles over zeros in loop transmission). The fast tracking response can be obtained with linear compensator. But no strictly proper linear feedback can achieve fast tracking response when “d” can be bigger than1 or when gain k goes to infinity. Fast tracking with less control effort can be achieved when using quasi-linear [14].With these examples we come back to the position/velocity control problem. The same approach could be effectively adopted with certain conditions and constraints. The feedback linearized system has stable poles. For improved performance, the zero of the compensator (parameter a) has to be chosen according to this stable pole. A Comparable value of a with respect to the location of stable pole may result in pole-zero cancellation and hence an unacceptable response, whereas a larger value results in instability, however a sufficiently smaller value leads to a desired behavior. In this work, a suitable value of the stable zero is found to be at -1. Here a quasi-linear design is presented which has been obtained after considerable search and tuning over the parameter space. It is given by:

$$G_{k(ql)}(s) = K\frac{(s+a)}{(s+2K^{f})} \qquad (13)$$

Where $0 < f < 1$ and $k > 0$.

Equations (10) to (13) are used for showing the validity of controller in general [14], whereas its application for robot joint model is given in section IV

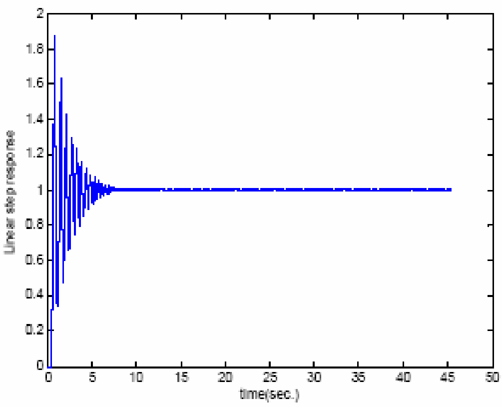

Fig.3 Response of the closed loop system with a linear compensator

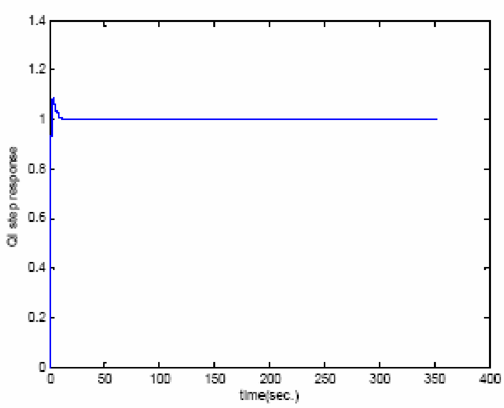

Fig. 4 Response of the closed loop system with a quasi-linear Compensator

IV. SIMULATION FOR THE SHOULDER JOINT OF HUMANOID ROBOT.

A. Controller Design

This section describes the implementation and effectiveness of the proposed control strategy. Quasi-linear controller is applied for a linearized open-loop System-dynamics model for the electromechanical shoulder joint/link, actuated by DC motor as shown in fig.5.

To verify the efficiency of the proposed scheme, Simulations are performed on robot shoulder joint system. Simulations on joint model are done using Matlab/Simulink, where the control loops and the model of shoulder joint are composed of Matlab/Simulink block sets. For position/velocity control of a robot joint, quasi-linear control algorithm is

$$G_{k(ql)}(s) = K\frac{(s+a)}{(s+2K^{f})}, \text{ where } a = 1,\ f > 0.1,\ k > 100$$

Simulations are shown in fig.6, fig.7 and fig. 8; confirm the better tracking property, and showing the validity of our proposed control strategy.

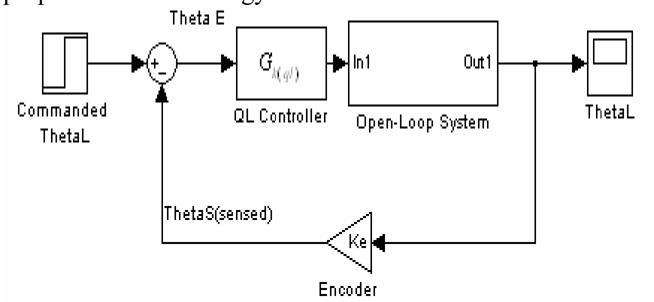

Fig.5 Closed loop feedback control diagram

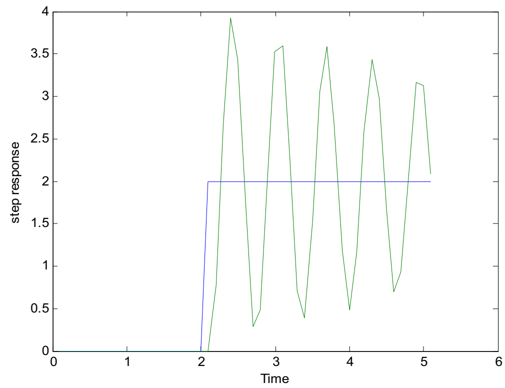

Fig.6a step response using Linear Compensator

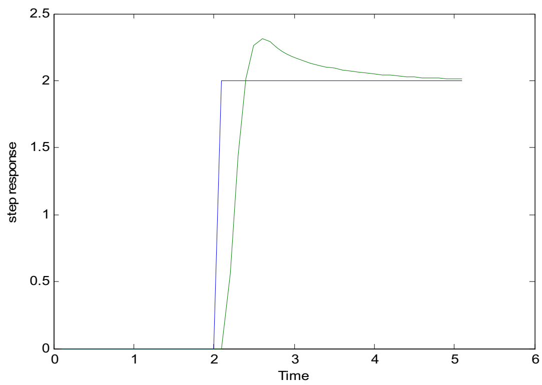

Fig.6b step response using ql compensator

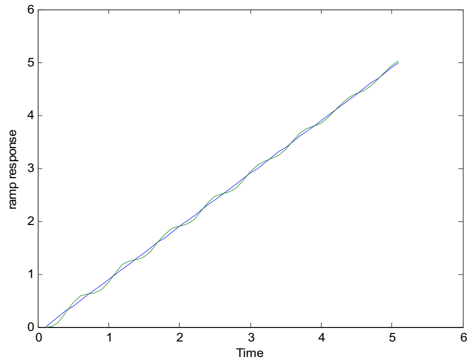

Fig.7a ramp response using linear compensator

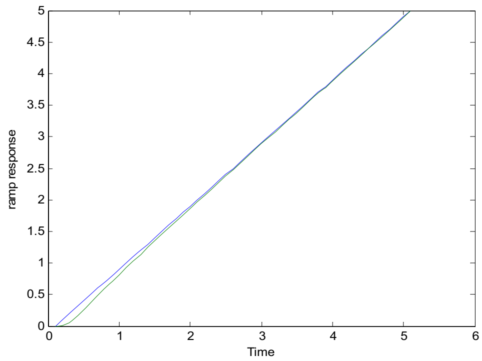

Fig.7b ramp response using ql compensator

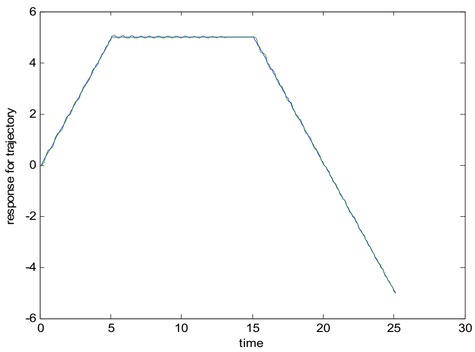

Fig. 8a trajectory response for linear compensator

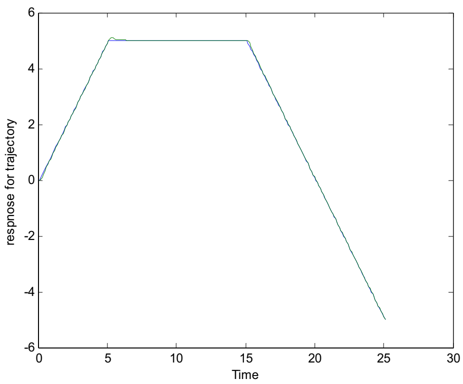

Fig.8b trajectory response for ql compensator

B) Observer Design:

The differentiation of a signal always decreases signal to noise ratio, because noise generally fluctuates more rapidly than the command signal. Sometimes the signal-to-noise-ratio may be decreased by several times by a single differentiation process.

Methods are available to estimate unmeasured state variables without a differentiation process. In this work, we measure the relative position in joint model and then estimate the relative velocity and acceleration of the model. We have designed a state observer, which provides the estimates of unmeasured states. We compare the performance results and observe the effects of employing an observer. The block diagram for complete simulation is given as Fig.9. With a choice of suitable poles for the observer, the gain matrix Ke is computed by pole placement method. However we assign the poles such that the resultant closed loop system has constrained μ in accordance with the physical limitations.

Thus the control law would take the form:

The robot joint is considered with coefficient of linear model as under:

$I_m = 0.2$, $b_m = 0.1$ $b = 0.6$ and $\eta^2 = 4$. Hence model in (9) reduces to:

$$\theta(s)/\tau(s) = 1/(2.8s+1)s \tag{14}$$

The system thus takes the form which can be described by the following standard equations:

$$\dot{X} = Ax(t) + Bu(t) \quad \text{where} \quad R^{2*2}$$

$$Y = Cx(t) \tag{15}$$

$$A = \begin{bmatrix} 0 & 1 \\ 0 & -0.36 \end{bmatrix},\ B = \begin{bmatrix} 0 \\ 0.35 \end{bmatrix},\ C = \begin{bmatrix} 1 \\ 0 \end{bmatrix}^T$$

The system described by equations (9) through (15) is observable since the observability matrix

$\begin{bmatrix} C^T & A^T C^T \end{bmatrix}$ is full rank

The control signal μ is given by

$$\mu = K\,x \tag{16}$$

The state feedback gain matrix k and k_e can be obtained

$$K = \begin{bmatrix} 11.2 & 6.9 \end{bmatrix} \text{ and } K_e = \begin{bmatrix} 7.64 \\ 13.25 \end{bmatrix},$$

Which are shown in simulation diagram as described in fig. 9

The simulations for similar set of conditions are performed on the new system. For nominal system the values are chosen as expected, a slightly degraded performance is observed as a result of using estimated states for feedback. The performance of the system can be observed as a result of using estimated state x_2 for feedback as shown in Fig.10.

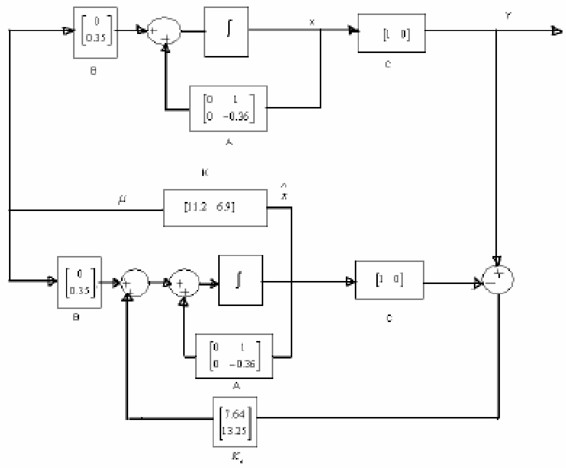

Fig.9 Simulation diagram of close loop control system with state observer.

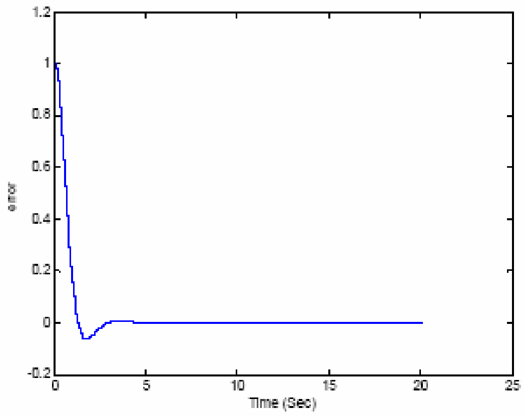

Fig.10 Response of the system with state estimator, to bring the error to zero

V. CONCLUSIONS

In this paper the approach is basically a quasi-linear control method combined with a state observer for robot joint model. Our controller based on the quasi-linear theory guarantees arbitrarily fast and robust tracking of the desired response, however our goal was to achieve suitably fast response and to reduce noise signal ratio using state observer for satisfactory performance. The controller is minimal order and is able to produce desirable results. Comparison to other linear control approaches can also be made; the quasi-linear control is superior to the classical linear approach. We tested the control system behavior for evaluating the tracking performances and found a minimal order quasi-linear controller with very good dynamic performances. The system performance is also checked using state observer. Simulations results show that propose approach provide better results for robot joint model.

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