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CONTROL SYSTEM DESIGN OF SPATIAL DISORIENTATION TRAINER

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Abstract

The spatial disorientation trainer (SDT) is a dynamic flight simulator used to enhance ability of pilots of modern combat aircrafts to deal with dangerous effects of spatial disorientation. This device can be modeled and controlled as 4DoF robot manipulator. In this paper, control system design of SDT based on a dynamic model is presented. Two control strategies are compared: 1) computed torque method with feedforward compensation of nonlinearities and cross-coupling effects in dynamic model; 2) single joint (decentralized) PD position controller. PD controller is designed for the actuator model which includes inertia reflected on rotor shafts (effective inertia). Position feedback design considers structural natural frequencies of the manipulator. Effective inertias of SDT for commanded motions are obtained from robot inverse dynamic model which is developed using recursive Newton-Euler equations. Simulation of position tracking for commanded motion is performed in Matlab Simulink.

Key words: spatial disorientation trainer, robot control, computed torque, inverse dynamics

1. Introduction

According to its most widely used definition, one that has been accepted by a large number of countries, spatial disorientation refers to: a failure to sense correctly the position, motion or attitude of the aircraft or of him/her within the fixed coordinate system provided by the surface of the earth and the gravitational vertical [1]. Spatial disorientation is one of the major threats to pilots of modern fighter aircraft [2]. The spatial disorientation trainer (SDT) examines a pilot's ability to recognize unusual flight orientations, to adapt to unusual positions and to persuade the pilot to believe in the aircraft instruments for orientation and not in his own senses [3]. In this paper, SDT designed in Lola Institute is considered [2-3]. Virtual structure of the SDT is made in CATIA, Fig. 1.

Fig. 1 SDT of four degrees of freedom

Arm rotation around the vertical (planetary) axis is the primary motion. The arm carries a gyroscopic gondola system with three rotational axes providing yaw, pitch and roll capabilities. The yaw axis (z) is parallel with the arm axis. The roll (*x* axis) lies in the plane of the arm rotation. The pitch (y) axis is perpendicular to the roll axis [3]. Through rotations about these axes, different orientations can be achieved; different acceleration forces acting on the pilot can also be simulated. The SDT is modeled and controlled as a 4DoF robot manipulator with revolute joints.

The main challenge in the motion control problem of rigid manipulators is the complexity of their dynamics and uncertainties. The former results from nonlinearity and coupling in the robot manipulators, while the latter is twofold: structured uncertainties due to imprecise knowledge of the dynamic parameter; unstructured due to joint and link flexibility, actuator dynamics, friction, sensor noise, and unknown environment dynamics [4]. During design of control systems of robot manipulators, special attention is paid to inclusion of dynamic model into control that would result in satisfactory performance, and in the same time would not significantly increase complexity of control system. Joint space control techniques can be classified in decentralized control schemes, when the single manipulator joint is controlled independently of the others and any coupling effects due to the motion of the other links is treated as disturbance, and centralized control schemes, when the dynamic interaction effects between the joints are included in control algorithms [5].

When deciding which control methodology should be implemented, it is advisable to account applications in which particular robot manipulator will be used. After development of trajectory planner/interpolator based on a kinematic model, desired profiles of joint trajectories (paths, velocities and accelerations) for a given application program, that provide a first indication of which type of control method should be used, are obtained. In the case of slow trajectories, it can be assumed that the influence of dynamic forces due to nonlinearities and cross-coupling terms upon the positioning and tracking is not significant and, therefore, the servos based on feedback controllers synthesized for isolated joints of the robot can easily overcome them. In case when fast trajectories (with large and/or sudden change in velocity and/or acceleration) are required, i.e. when process variations are large, designing a linear controller that gives a robust system with good performance could be challenging task. However, control methodology choice cannot be based on joint trajectories only. After obtaining time sequences of joint positions, velocities and accelerations as the outputs of trajectory planner, inverse dynamics algorithm (ID) computes the torques to be applied to the joints in order to obtain joint's commanded motions. This computation is useful for proper choice of robot actuators, verifying the feasibility of imposed trajectory, computer simulation, in model based control methods etc. A complete ID model for SDT is given in [3] in the form of recursive Newton-Euler equations.

In this paper, control system design of SDT based on a dynamic model is presented. Computed torque method [7], in which feedforward compensation of nonlinearities and cross-coupling effects of dynamic model is performed, is considered as control strategy. PD position controller is added to feedforward compensator to provide robustness to the model uncertainty and reduction of disturbance effects. This method is compared to traditional decentralized (single joint) PD position controller. Actuator modeling is based on effective inertias (inertias reflected on the rotor shafts) which are calculated from ID for desired joint trajectories. Position feedback design considers structural natural frequencies of manipulator. Matlab Simulink models are designed to simulate position tracking achieved by aforementioned two types of controllers.

This paper is organized as follows. In second section, trajectory planner of SDT manipulator is described. In Section 3, methodology used for design of motion control system of SDT based on ID is presented. Results and discussion is given in Section 4. Conclusion is given in section 5.

2. Trajectory planner of SDT

Required task for SDT manipulator is to achieve commanded orientation in the center of the gondola, where the pilot's chest or head is placed. Commanded motion is given in application program in Lola Industrial Robot Language (L-IRL) modified for flight simulators [8]. Developed direct and inverse kinematics algorithms and inverse and forward dynamic models are presented in [3]. An approximate inverse dynamics algorithm given in [3], which accounts for the motors present in the system, is implemented in trajectory planner. Trajectory planner for SDT is implemented in L-IRL. In Fig. 2, SDT joint trajectories obtained as outputs of trajectory planner are given for a typically commanded motion. In Fig. 3, information flow in SDT presented in this paper is given.

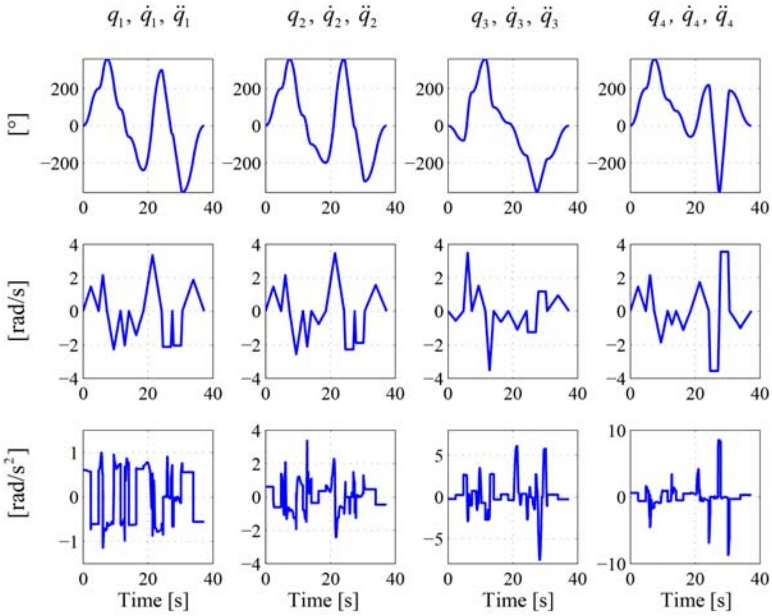

Fig. 2 Positions, velocities and accelerations of SDT joints

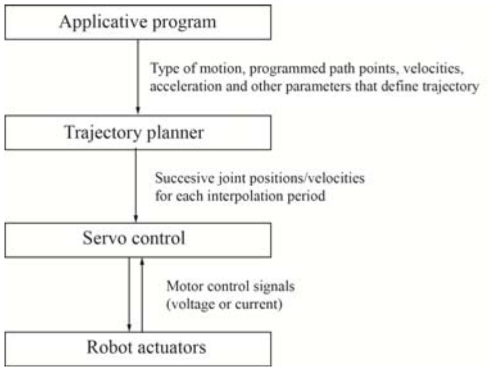

Fig. 3 Information flow in SDT

3. Dynamic model based design of control system of SDT

The manipulator dynamical model can be described by a well known set of n coupled nonlinear differential equations (1) for joints $k = 1..n$. τ_k is actuating torque for axis k. In the Newton-Euler method, the actuator driving torque $\tau_k = \hat{m}_{zk}$ is obtained as z_k component of vector $\hat{\boldsymbol{m}}_k$ - moment vector exerted on link k by link k-1 described in the frame attached to joint k [11].

$$\sum_{j=1}^{n} d_{jk}(\boldsymbol{q})\ddot{q}_j + \sum_{i=1}^{n}\sum_{j=1}^{n} h_{ijk}(\boldsymbol{q})\dot{q}_i\dot{q}_j + g_k(\boldsymbol{q}) = \tau_k \tag{1}$$

Following nonlinear time-variant actuator model can be obtained for the joint k:

$$J_{effk}\ddot{q}_{mk} + B_{effk}\dot{q}_{mk} = \tau_{mk} - T_{Lk} \tag{2}$$

Here, $\dot{q}_{mk} = r_k\dot{q}_k$ is angular speed of actuator's rotor, r_k is motor gear ratio, $\dot{q}_k$ is rotational speed of joint, τ_{mk} represents the total torque generated by the actuator, B_{effk} is reflected friction coefficient and J_{effk} is inertia reflected on the rotor shaft, denoted here as effective inertia. T_{Lk} represents load torque, which is of twofold nature: torque due to the motion of chain of interconnected links-$\hat{T}_{Lk}$ which can be calculated from dynamic model, and load torque due to stochastic disturbances-$\hat{T}_{LSk}$.

In this paper, actuator is modeled and load torque $\hat{T}_{Lk}$ is calculated based on a method given in [12]. Load torque $\hat{T}_{Lk}$, a part of a load torque T_{Lk} from (2), is obtained from ID (1) in following way:

$$\hat{T}_{Lk} = \left(\hat{m}_{zk} - \hat{d}_{kk}\ddot{q}_k\right)/r_k = \left(\sum_{j=1, j\neq k}^{n} \hat{d}_{jk}(\boldsymbol{q})\ddot{q}_j + \sum_{i=1}^{n}\sum_{j=1}^{n} \hat{h}_{ijk}(\boldsymbol{q})\dot{q}_i\dot{q}_j + \hat{g}_k(\boldsymbol{q})\right)/r_k \tag{3}$$

Inertial term $\hat{d}_{kk}\dot{\omega}_k$ from (1) is accounted for through inertia reflected on rotor shaft:

$$J_{effk} = \left(J_{mk} + \hat{d}_{kk}/r_k^2\right) \tag{4}$$

where coefficient of $\dot{\omega}_k$ in ID (1) is added to motor and gearbox inertia J_{mk}. In (3) and (4), the overline notation (hat ^) is used to denote that torque and torque terms in (1) are described in the frame attached to joint k (frame k-1 according to Denavit-Hartenberg convention).

Computed torque method implies feedforward cancelation of nonlinear coupling dynamic terms in (1). Here, load torque due to the motion of chain of interconnected links-$\hat{T}_{Lk}$ obtained from ID (3) is cancelled with feedforward signal. This control method would achieve ideal tracking in a case of ideal process modeling and calculation of (3). Given that modeling in practice is almost never error free, addition of feedback to presented feedforward control method is beneficially for improving the reference tracking capability of the controlled system.

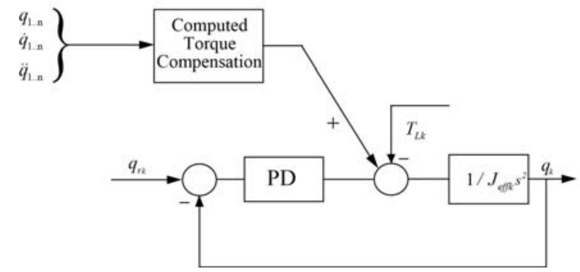

Fig. 4 Feedforward computed torque compensator with added PD position controller

If an accurate model for friction obtained by experiments is available, friction compensation can be introduced in a control. Otherwise an alternative approach, which is adopted in this paper, is to regard the bounded nonlinear friction terms as disturbances in traditional servo systems. In torque motors (which are chosen for actuating of axes 2, 3 and 4), friction problem is of much lesser significance compared with motors with gear reduction. With this approach, (2) becomes:

$$J_{effk}\ddot{q}_{mk} = \tau_{mk} - T_{Lk} \tag{5}$$

Purpose of this paper is to compare traditional decentralized single joint feedback control with computed torque control strategy for SDT. In order to account for resonant features of mechanical structure, PD position control is chosen as a decentralized control method. In this way, structural resonant frequencies could be considered. Transfer function of closed-loop system between controlled variable q_{mk} and control input is in the form:

$$W(s) = \left(K_{Pk} + K_{Dk}s\right) / (J_{effk}s^2 + K_{Dk}s + K_{Pk}) \tag{6}$$

where K_{Pk}, K_{Dk} are the proportional and derivative gains, respectively. Given that structural flexibilities in the system are not accounted for in a modeling, in order not to excite unmodeled resonances, a rule of thumb is used where lowest structural natural frequency ω_r is at least two times bigger than natural (undamped) frequency ω_n of the feedback system (6). [11].

A simple solution to overcome the problem of variable process control is to adopt time-invariant model, to tune controller for the biggest load and accept deteriorated performance at other operating conditions [6]. Given that effective inertia of a specific *k* joint's actuator (4) depends on on the instantaneous manipulator configuration, for a fixed proportional gain K_{Pk}, natural frequency of closed loop system (6) varies i.e. $\omega_n(\boldsymbol{q}) = \sqrt{K_{Pk} / J_{effk}(\boldsymbol{q})}$, and thus maximal value of natural (undamped) frequency is obtained for minimal value of effective inertia. However, considering request that the motion of the link is never underdamped, maximum value of effective inertia $J_{effk\max}$ (4) is used for obtaining critically damped response (damping ratio $\zeta = 1$ for $J_{effk\max}$). Thus, following must be valid:

$$K_{Dk} = 2\omega_{n\max k} J_{effk\max} = 2\sqrt{K_{Pk} J_{effk\max}} \tag{7}$$

where $\omega_{n\max k} = \sqrt{K_{Pk} / J_{effk\max}}$ is natural frequency of closed loop system when effective inertia is maximal. When controller is tuned so that response is critically damped for $J_{effk\max}$, in all configurations with smaller values of effective inertia, motions will be overdamped, and thus maximal value of effective inertia can be used for obtaining maximal value of proportional gain:

$$K_{Pk\max} = J_{effk\max}\omega_r^2 / 4 \tag{8}$$

When proportional gain is chosen, derivative gain follows from (7).

4. Results and discussion

For axis 1, an AC motor ([3, 9]) is chosen with a rated torque of $M_{1r} = 37\ Nm$, a rated number of revolutions $n_{1r} = 3000\ min^{-1}$, gearbox ratio 67.2, moment inertia of actuator is $J_{m1} = 291 \cdot 10^{-4}\ kgm^2$. Axes 2, 3 and 4 are actuated by torque motors. The motor for axis 2 has a rated torque $M_{2\mathrm{r}} = 2380\ Nm$, a maximum speed at that torque $\omega_{2r} = 8.38\ s^{-1}$ [3, 10] and moment of inertia $J_{m2} = 173 \cdot 10^{-2}\ kgm^2$. The motors for axes 3 and 4 [10] have a rated torques $M_{3\mathrm{r}} = M_{4\mathrm{r}} = 1350\ Nm$, a maximum speed at that torque $6.91\ s^{-1}$, and moments of inertia $J_{m3} = J_{m4} = 53.1 \cdot 10^{-2}\ kgm^2$.

From CATIA, ω_r=10.5028 Hz=65.99 rad/s is obtained as the lowest structural resonant frequency of SDT. For chosen actuators and trajectories given in Fig. 2, maximal values of effective inertias and maximal variations of effective inertias relative to maximal values are given in Table 1. Coefficients $\hat{d}_{kk}$ are obtained from ID (1) as the sum coefficients of of acceleration $\ddot{q}_k$. All allowed (possible) programmed motions of SDT should be taken into account, so that minimal and maximal values of load (effective inertias) are determined.

Joint	Maximal eff. inertia $J_{effk\max}$ [kgm^2]	Eff. inertia variations [%]	Actuator TF W_{Ak}	Gain K_{Pk}	Gain K_{Dk}
k=1	3.62	43.56	$1/3.62s^2$	$3.95 \cdot 10^3$	239.4
k=2	2704.8	18.51	$1/2704.8s^2$	$2.94 \cdot 10^6$	$1.79 \cdot 10^5$
k=3	796.35	7.3	$1/796.35s^2$	$8.67 \cdot 10^5$	$5.3 \cdot 10^4$
k=4	251.56	26.12	$1/251.56s^2$	$2.74 \cdot 10^5$	$1.66 \cdot 10^4$

Table 1. Process and controller parameters for joints k=1..4 for trajectory given in Fig. 2

For position PD controller, maximal values of proportional gains K_{Pk} (8) are chosen. Derivative gains K_{Dk} are chosen according to (7). Gains are given in Table 1.

Simulink models are designed in order to simulate and compare position tracking achieved by: 1) position feedback with PD controllers designed for processes with maximal loads (maximal effective inertias) given in Table 1; 2) feedforward computed torque method with the same feedback controllers. In Simulink models, the reference position is given as a series of discrete values obtained from the trajectory planner, given in Fig. 2.

In simulation of position tracking with first method (PD position feedback), disturbance is simulated through load torque $\hat{T}_{Lk}$, k=1..4 which is calculated from ID (3) for every interpolation period. Position tracking of joints k=1..4 with controllers designed for maximal loads and when processes are modeled as linear time-invariant (LTI) systems with maximal values of effective inertias, are given in Fig. 5. In Fig. 6, errors $e_k = q_{rk} - q_k$, k=1..4 , where q_{rk} is reference value, in position tracking when minimal and maximal values of effective inertias are used in LTI process models (5), and with controllers designed for maximal loads are given. Errors of time-variant actuator model should be between these curves (red is for position error when minimal value of effective inertia used in actuator model).

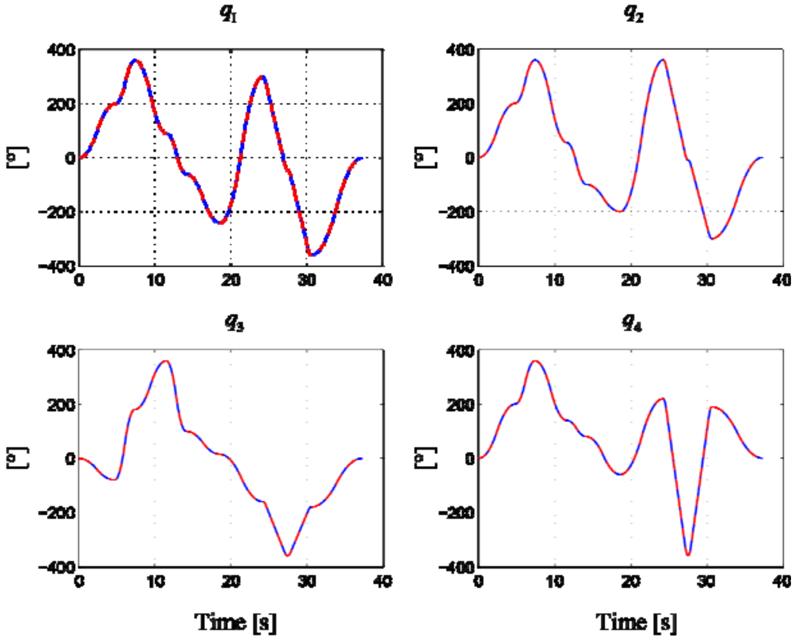

Fig. 5 Position tracking with PD controller for LTI actuators models with maximal values of effective inertia (blue color-reference value q_{rk}, k=1..4)

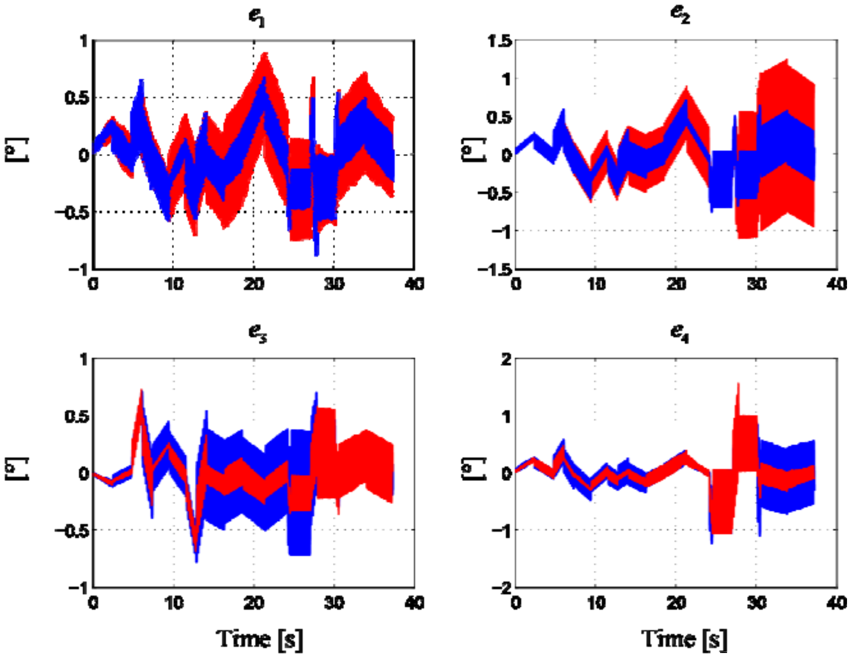

Fig. 6 Errors for LTI process models with minimal and maximal values of effective inertia (blue color-maximal values of effective inertia) with PD position tracking

In Simulink model used for simulation of tracking with computed torque strategy, total load torque T_{Lk}, k=1..4 is simulated as $T_{Lk} = \hat{T}_{Lk}\left(1 + A\sin\omega_D t\right)$. Term $\hat{T}_{Lk} A\sin\omega_D t$ simulates stochastic disturbances and uncertainties (errors in estimates of load torque $\hat{T}_{Lk}$). Here, t stands for time, while values A and ω_D simulate amplitude and frequency of disturbances. Load torque $\hat{T}_{Lk}$, k=1..4 is compensated for every interpolation period. Same PD position controllers are used as in previous simulation, and LTI process models with maximal effective inertia. In Fig. 7, the errors e_k, k=1..4 obtained by computed torque method, for chosen values for $A = 0.05$ (which suggest that load torque estimation error is about 5 %) and $\omega_D = 100$ are given in red color. In the same figure, errors e_k, k=1..4 obtained by previously described PD position controller are given in blue color. As it can be seen, errors obtained by computed torque method insignificantly differ from errors obtained by traditional PD position compensator, and in some segments, they are even slightly larger (which can be explained by error in load torque estimation).

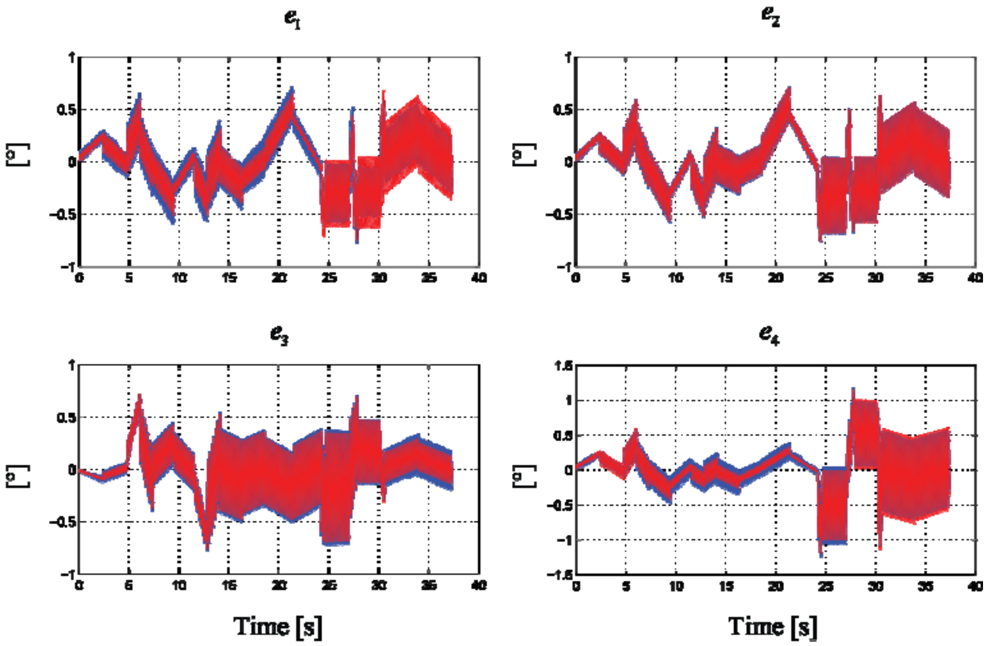

Fig. 7. Errors in position tracking with computed torque method (red color) and PD position feedback (blue color), $A = 0.05$, $\omega_D = 100$

Given that commanded motion in Fig. 2 requires small values of velocities, improvement is not obtained by implementing computed torque control. However, if velocities from Fig.2 are multiplied by 20, the errors e_k, k=1..4 obtained by computed torque method, for chosen values for $A = 0.125$ (which suggest that load torque estimation error is about 12.5 %) and $\omega_D = 100$ are given in red color in Fig. 8. In the same figure, errors e_k, k=1..4 obtained by previously described PD position controller are given in blue color. As it can be seen, errors obtained by computed torque method are significantly smaller.

In Fig. 9, comparison if position tracking with computed torque method and tradition position PD controller, when accelerations of joints from Fig.2 are multiplied by 50, $A = 0.125$, $\omega_D = 100$ is given. It should be noted that in simulations with multiplied velocities/accelerations-Fig. 8 and Fig 9., LTI process models with maximal effective inertias obtained for trajectories with new (multiplied) velocities/accelerations and new PD position controllers obtained from (7) and (8) are used.

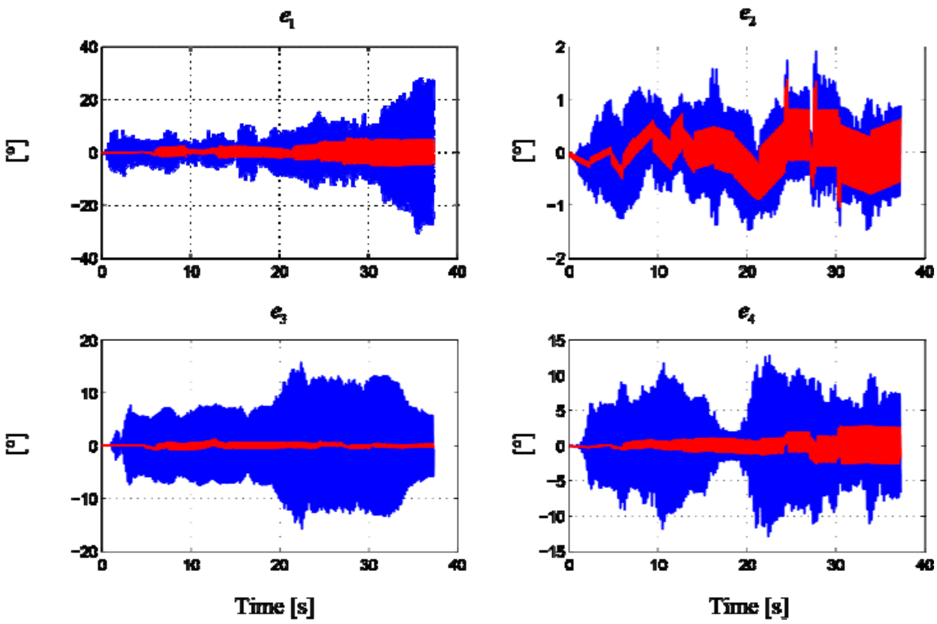

Fig. 8. Errors in position tracking with computed torque method (red color) and PD position feedback (blue color), $A = 0.125$, $\omega_D = 100$, velocities x 20

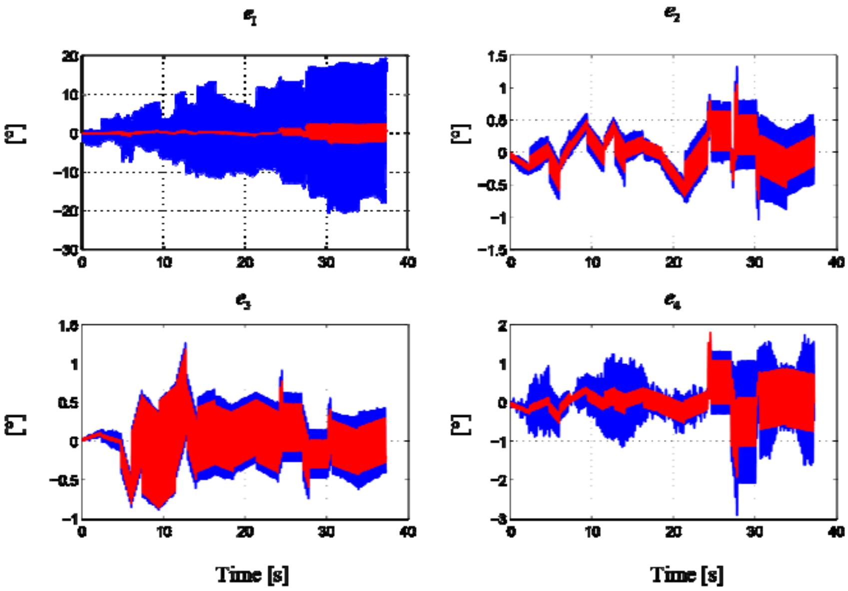

Fig. 9. Errors in position tracking with computed torque method (red color) and PD position feedback (blue color), $A = 0.125$, $\omega_D = 100$, acceleration x 50

From Figs. 7-9, it can be concluded that improvement in position tracking for SDT with computed torque method would be significant in a case of much higher velocities, even with relatively significant errors in estimates of the total load torque T_{Lk}.

5. Conclusions

In this paper, design of control system of SDT based on a dynamic model is presented. Feedforward computed torque method with compensation of nonlinearities and cross-coupling

effects in dynamic model, is considered, and it is compared with the traditional PD position controller. Position feedback design considers structural natural frequencies of manipulator, as well as request that the motion of the link is never underdamped.
It is determined that, since motions of SDT do not require large values of velocities, improvements in tracking obtained by more complex computed torque method compared to traditional PD position controller, are not significant. For better tracking, additional controllers should be investigated.

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