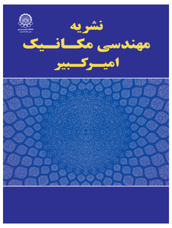

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Active fault tolerant control based on adaptive back-stepping nonsingular fast integral terminal sliding mode approach

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ABSTRACT: In this paper, finite-time active fault tolerant control based on adaptive back-stepping nonsingular fast integral terminal sliding mode control is proposed to control a lower limb exoskeleton in the presence of actuator fault. In order to detect, isolate and accommodate the actuator fault, a third-order super twisting sliding mode observer is used. To eliminate the chattering of conventional sliding mode, supper twisting sliding mode algorithm is applied, which leads to finite-time convergence and high precision in tracking the desired trajectories. Back-stepping term guarantees global stability based on Lyapunov theory. Upper limb motion is used to provide stability to robot's motion based on zero-moment point criterion. In order to attain maximum stability based on zero-moment point, minimize error in tracking the desired trajectories, increase the tolerance of the controller against actuator fault, controller, observer and upper limb trajectory parameters are optimally tuned based on harmony search algorithm. Performance of the proposed controller is compared with the performance of sliding mode controller with/without fault information. Simulation results reveal the effectiveness of the proposed controller in the presence of actuator fault, uncertainty and disturbance in comparison with sliding mode controller.

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1- Introduction

Exoskeletons have been essentially employed to increase human physical performance in military purposes, rehabilitation and medical applications. Conformity with the human body and also control strategies applied to exoskeletons have immense impacts on the performance of these means [1]. To counteract the faults of the system, compensate for the effect of un-modeled dynamics, uncertainties and disturbances from the user and the environment, and to reduce the metabolic cost imposed on the user, choosing an appropriate control strategy for exoskeletons is of high importance. Sliding Mode Controller (SMC) is a robust approach which is developed in recent years [2]. Despite its robustness against uncertainties and disturbances, it suffers from low convergence rate, low performance against high rate disturbances, relying on the bounds of uncertainties and disturbances, and chattering phenomenon [3].

Fault-Tolerant Control (FTC) is developed to maintain system safety and an acceptable level of performance in the presence of faults [4]. Generally, FTC is categorized as Passive FTC (PFTC) and Active FTC (AFTC).

Different approaches have been employed for fault detection and estimation in the context of nonlinear systems and robotics. The high order super-twisting observer used for fault detection and isolation offers two main advantages. I) Speed estimation without using filters, II) using the capabilities of high order SMC in identifying unknown inputs [5].

The main contribution of this paper is to design an adaptive FTC by combining adaptive back-stepping nonsingular fast terminal integral-type sliding mode controller and super twisting third-order observer for a 7-DOF lower limb exoskeleton. This controller offers high convergence, fast transient response, stability based on Lyapunov theory and eliminated chattering. To compensate for the effect of disturbances and uncertainties with unknown bounds an adaptive law is used.

2- Problem Statement

In this paper, an adaptive FTC based on back-stepping nonsingular fast terminal integral type SMC is designed to counteract the faults of the system, compensate the effect of un-modeled dynamics, uncertainties and disturbances from the user and the environment. For adaptive FTC, super-twisting third-order observer is employed. Walking stability of the robot at each moment is studied utilizing ZMP criterion and to achieve maximum stability margin, the motion of the upper limb joint is used.

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2- 1- Problem formulation

To reach a harmonious motion between the robot and the user, in this paper a 7-DOF mechanism is chosen whose joints are placed on the user's hip, knee and ankle joints. the dynamic equation of the robotic expressed as Eq. (1) [2].

$$\begin{aligned}\tau &= M(\theta)\theta'' + C(\theta,\theta') + G(\theta) + F(\theta') + \tau_d \\ &+ \beta(t-T_f)\varphi(\theta,\theta',\tau) + \Delta(\theta,\theta',t)\end{aligned} \tag{1}$$

where τ is the actuators torque, $M(\theta)$, $C(\theta,\theta')$ are the matrices of inertia moment, and centrifugal and gyroscopic effects, $G(\theta)$ and $F(\theta')$ represent gravitational and friction force vectors, respectively. Additionally, τ_d and $\Delta(\theta,\theta',t)$ denote disturbance torque and uncertainty vectors, and $\beta(t-T_f)\varphi(\theta,\theta',\tau)$ define actuator fault vector.

2- 2- Adaptive back-stepping nonsingular fast integral type terminal sliding mode controller

For high convergence rate and fast transient response, a nonsingular fast terminal integral-type sliding surface is chosen as [3]:

$$S_1 = \int (e + \mathrm{k}_1 e^{\lambda} + \mathrm{k}_2 \dot{e}^{p/q})\,dt \tag{2}$$

where k_1 ,k_2 , and$\lambda$are positive constants. The third order state space equations are written as:

$$\begin{aligned}\dot{S}_1 &= S_2 \\ \dot{S}_2 &= S_3 \\ \dot{S}_3 &= \frac{d}{dt}\left(\dot{e} + \mathrm{k}_1\lambda|e|^{\lambda-1}\dot{e} + \mathrm{k}_2\frac{p}{q}|\dot{e}|^{\frac{p}{q}-1}(\theta'' - \ddot{q}_d)\right)\end{aligned} \tag{3}$$

Here, $\ddot{q}_d$ denotes desired acceleration of robot joints. To design the controller based on backstepping method, new state variables are defined as [2]:

$$\begin{aligned}\upsilon_1 &= S_1 \\ \upsilon_2 &= S_2 - \alpha_1 \\ \upsilon_3 &= S_3 - \alpha_2\end{aligned} \tag{4}$$

The back-stepping non-singular fast terminal integral-type sliding mode control law is proposed as follows:

$$\begin{aligned}U &= \frac{M(\theta)}{\Xi}(U_n - U_s) \\ U_n &= \Xi\ddot{q}_d + \Xi M^{-1}(\theta)[C(\theta,\theta')\theta' + G(\theta)] + \alpha_2 \\ &-\psi - \int(\xi_3\upsilon_3 - \upsilon_2)\,dt \\ \dot{U}_s &= (A + \xi)\mathrm{sign}(\upsilon_3) \\ \psi &= \dot{e} + \mathrm{k}_1\lambda|e|^{\lambda-1}\dot{e} \\ \Xi &= \mathrm{k}_2\frac{p}{q}|\dot{e}|^{\frac{p}{q}-1} \\ \alpha_1 &= -\xi_1\upsilon_1 \\ \alpha_2 &= -\xi_2\upsilon_2 - \upsilon_1 - \xi_1 S_2\end{aligned} \tag{4}$$

An adaptive back-stepping nonsingular fast integral type terminal sliding mode control law is proposed as:

$$\begin{aligned}U &= \frac{M(\theta)}{\Xi}(U_n - U_{as}) \\ \dot{U}_{as} &= (\widehat{A} + \xi)\mathrm{sign}(\upsilon_3) \\ \widehat{A} &= \frac{1}{\delta}|\upsilon_3|\end{aligned} \tag{5}$$

To prove the stability of the proposed control law, Lyapunov function is considered as Eq. (6).

$$V_4 = V_3 + \frac{1}{2}\delta(A - \widehat{A})^2 \tag{6}$$

Differentiating Eq. (6) with respect to time yields,

$$\begin{aligned}\dot{V}_4 &= -\xi_1|\upsilon_1|^2 - \xi_2|\upsilon_2|^2 + \upsilon_2\upsilon_3 \\ &+\upsilon_3\frac{d}{dt}\left(\dot{e} + \mathrm{k}_1\lambda|e|^{\lambda-1}\dot{e} + \mathrm{k}_2\frac{p}{q}|\dot{e}|^{\frac{p}{q}-1}(\theta'' - \ddot{q}_d) - \dot{\alpha}_2\right) \\ &+\delta(\widehat{A} - A)\dot{\widehat{A}} \\ \dot{V}_4 &\le -\xi_1|\upsilon_1|^2 - \xi_2|\upsilon_2|^2 - \xi_3|\upsilon_3|^2\end{aligned} \tag{7}$$

Thus, the proposed control law is asymptotically stable.

2- 3- Third order super twisting observer for state estimation and fault detection

Based on Eq. (1), state-space equations can be written as Eq. (8).

$$\begin{aligned}x_1 &= \theta \\ x_2 &= \theta' \\ \dot{x}_1 &= x_2 \\ \dot{x}_2 &= f(x_1, x_2, \tau) + \tilde{\Delta} + \beta(t-T_f)\varphi(\theta,\theta',\tau) \\ f(x_1, x_2, \tau) &= M^{-1}(\theta)(\tau - C(\theta,\theta') - G(\theta)) \\ y &= x_1\end{aligned} \tag{8}$$

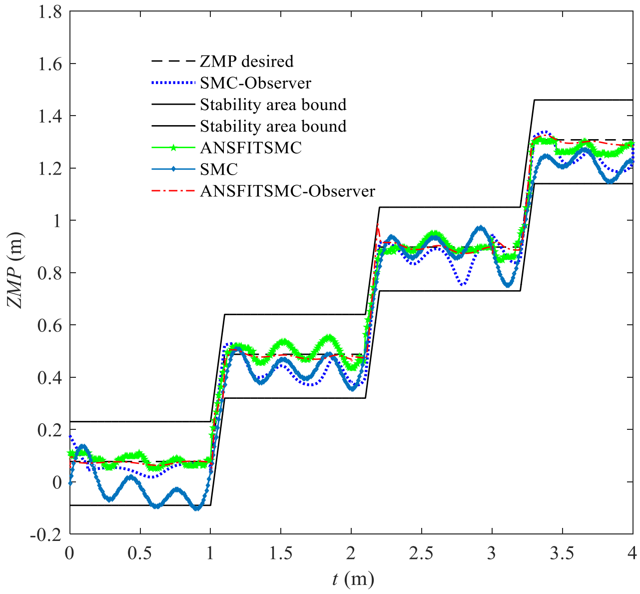

Fig. 1 ZMP position

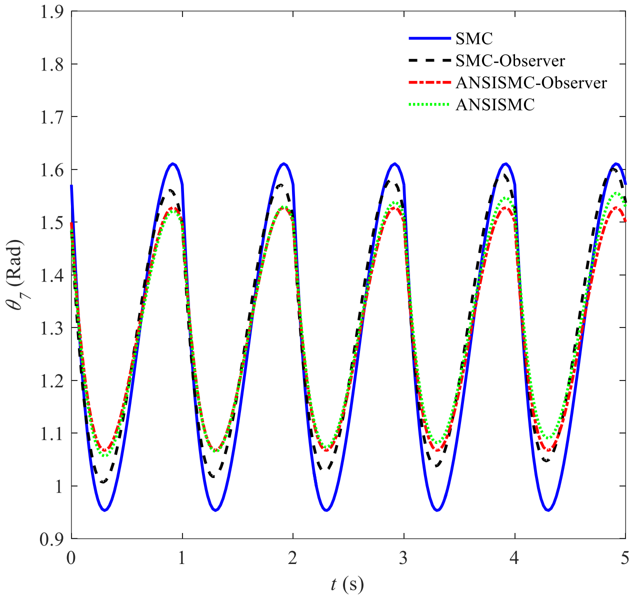

Fig. 2 The desired trajectory for the upper limb joint

A third-order super twisting sliding mode observer is presented as [5]:

$$
\begin{aligned}
&\dot{\hat{x}}_1 = \hat{x}_2 + \alpha_2 \left\| x_1 - \hat{x}_1 \right\|^{2/3} \operatorname{sign}(x_1 - \hat{x}_1) \\
&\dot{\hat{x}}_2 = f\,(x_1, \hat{x}_2, \tau) + \alpha_1 \left\| \dot{\hat{x}}_1 - \hat{x}_2 \right\|^{1/2} \operatorname{sign}(\dot{\hat{x}}_1 - \hat{x}_2) + \hat{z}_{eq} \qquad (9) \\
&\dot{\hat{z}}_{eq} = \alpha_0 \operatorname{sign}(\dot{\hat{x}}_1 - \hat{x}_2)
\end{aligned}
$$

where, α_i are the sliding gains and are obtained during controller design. The active fault-tolerant control is designed as:

$$
U = \frac{M(\theta)}{\Xi}\left(U_n - U_{as} + \Xi \hat{Z}_{eq}\right) \qquad (10)
$$

3- Results

In this paper, white noise with 20 percent amplitude of the control signal is applied to each joint, and 20% uncertainties in parameters are applied to the model. At and actuator faults are also imposed as a function of joint positions and velocities. The performance of the AFTCis studied using ZMP location (Fig. 1), and upper limb joint trajectory (Fig. 2).

As is shown in Fig. 1, the ZMP trajectory produced by the AFTC is closer to the desired one, and as a result, generates a greater stability margin.

4- Conclusions

In this paper, the performance of the proposed AFTC has been compared with adaptive back-stepping nonsingular fast integral type terminal sliding mode control as a PFTC approach, and conventional SMC scheme. The results show that the AFTC outperforms the others in tracking the desired joint trajectories, convergence rate, interacting forces between human and the robot, control effort, motion stability based on ZMP criterion, as well as robustness against disturbances, uncertainties and faults.

References

[1] G. Chen, Y. Song, F. Lewis, Distributed Fault-Tolerant Control of Networked Uncertain Euler–Lagrange Systems Under Actuator Faults, IEEE Transactions on Cybernetics, 47(7) (2017), 1706- 1718.

[2] R. Wang and J. Wang, Passive Actuator Fault-Tolerant Control for a Class of Over Actuated Nonlinear Systems and Applications to Electric Vehicles, IEEE Transactions on Vehicular Technology, 62(3) (2013) 972-985.

[3] J. J. Gertler, Survey of model-based failure detection and isolation in complex plants, IEEE Control Systems Magazine, 8(6) (1988) 3–11.

[4] M. Van, S. S. Ge and H. Ren, Finite Time Fault Tolerant Control for Robot Manipulators Using Time Delay Estimation and Continuous Nonsingular Fast Terminal Sliding Mode Control, IEEE Transactions on Cybernetics, 47(7) (2017) 1681-1693.

[5] L. M. Capisani, A. Ferrara, A. Ferreira, L. M. Fridman, Manipulator fault diagnosis via higher order slidingmode observers, IEEE Transactions on Industrial Electronics, 59 (10) (2012) 3979–3986.

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