The 2017 World Congress on
Advances in Nano, Bio, Robotics and Energy (ANBRE17)
28 August - 1 September, 2017, Ilsan(Seoul), Korea

Robust control of a newly designed cable-driven manipulator using time delay estimation

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ABSTRACT

For the trajectory tracking control problem of a newly designed cable-driven manipulator under complex unknown disturbance, a nonlinear robust control method based on time delay estimation (TDE) is proposed and investigated. The core idea of this method is building the basic architecture of the controller using TDE and realizing the online estimation and real-time compensation of the complex unknown lumped dynamics for the closed-loop control system. Afterwards, the control performance is regulated with the designed desired dynamics equation. Benefitting from the compensation of the unknown lumped dynamics and the model-free nature of TDE, the proposed method has good robustness and practical easy usage. Finally, the effectiveness of the proposed method was demonstrated through an experiment.

1. INTRODUCTION

In recent years, the robot manipulators have attracted lots of attention in both the academic and industrial fields thanks to their good ability of handling automatic task (Wang 2017). Benefiting from their fast speed, high precision and efficiency, the traditional robot manipulators have been widely used in manufacturing, logistics, medical treatment, even home entertainment fields. However, there are still some disadvantages of traditional robot manipulators: 1) the mass of the moving arm is quite large; 2) the flexibility is poor leading to low safety for human-robot interaction; 3) the load-to-weight ratio is low.

To effectively solve above-mentioned problems, the cable-driven manipulators had been proposed (Townsend 1988). By removing the drive units from the joints to the base, the cable-driven manipulator can effectively reduce the mass of the moving arm

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and improve the load-to-weight ratio and flexibility. Townsend proposed a novel cable-driven 7 degree of freedom (DOF) manipulator named "WAM" (Townsend 1988). Thanks to this new drive unit design, the proposed manipulator can obtain good working performance, and it is widely used in medical treatment (Phan 2014), industry applications (Saric 2014) et al. Thomas et al proposed a light 4-DOF flexible manipulator "BioRob-Arm" which can ensure a precision of 1mm with 2kg payload (Lens 2010, Lens 2012). Chen et al designed a novel 7 DOF cable-driven humanoid-arm robot (CDHAR) which is based on the hybrid structure of serial-parallel (Chen 2010, Chen 2013).

Inspired by aforementioned achievements, we designed a novel 7-DOF cable-driven manipulator named "Polaris-I". Its fore 4-DOF use the cable-driven technique to effectively reduce the moving mass, while the tail 3-DOF use the motor for direct driven. This structure can greatly reduce the complexity of the kinematic couplings; while still ensure a low moving mass and good flexibility.

Due to the adoption of cable-driven technique, the controller design for cable-driven manipulators can be a challenging job considering the complex unknown lumped disturbance. To obtain satisfactory control performance and keep the simplicity for practical applications, a nonlinear robust control method based on the time delay estimation (TDE) technique is proposed and investigated in this paper. Using the intentionally time-delayed information of the closed-loop control system, the TDE can effectively estimate and compensate the complex unknown lumped disturbance for the system with a simple matter. Afterwards, the system control performance is regulated using the designed desired dynamics equation. Thanks to TDE, the proposed control method is model-free and easy to apply in practical applications. Meanwhile, the required control gains for the desired dynamics equation are effectively reduced since most of the unknown system dynamics is compensated by the TDE. Finally, an experiment had been conducted to verify the effectiveness of our proposed controller.

2. MAIN RESULTS

2.1 Dynamics of a cable-driven manipulator

The dynamics of a cable-driven manipulator can be given as (Jin 2017, Alessandro 2005):

$$I\ddot{\theta}+D_m\dot{\theta}=\tau_m-\tau_s\left(q,\dot{q},\theta,\dot{\theta}\right) \tag{1}$$

$$M\left(q\right)\ddot{q}+D_L\dot{q}+C\left(q,\dot{q}\right)+G\left(q\right)=\tau_s\left(q,\dot{q},\theta,\dot{\theta}\right)+\tau_d \tag{2}$$

$$\tau_s\left(q,\dot{q},\theta,\dot{\theta}\right)=K_s\left(\theta-q\right)+D_s\left(\dot{\theta}-\dot{q}\right) \tag{3}$$

where θ and q are the angular position vectors of the motors and the links, respectively, I stands for the motor inertia, D_m represents the motor damping matrix, τ_m stands for the motor input torque, while $\tau_s\left(q,\dot{q},\theta,\dot{\theta}\right)$ stands for the joint compliance torque given in Eq.(3). M(q) is a mass-inertia matrix of robot links which is diagonal, D_L stands for the viscous friction matrix, $C\left(q,\dot{q}\right)$ stands for the Coulomb friction and Coriolis and centrifugal forces vector of the robot links, G(q) stands for the gravitational force vector, and τ_d represents the unknown but bounded external disturbance. K_s and D_s stand for the matrices of joint stiffness and damping, respectively.

Substituting Eq.(2) into Eq.(1), the above dynamic equation can be rewritten as

$$\tau_m = I\ddot{\theta} + D_m\dot{\theta} + M(q)\ddot{q} + D_L\dot{q} + C(q,\dot{q}) + G(q) - \tau_d \tag{4}$$

Equation (4) can be further transformed into following form by introducing a constant gain $\bar{M}$

$$\tau_m = \bar{M}\ddot{q} + H \tag{5}$$

where H stands for the lumped unknown dynamics of the cable-driven manipulator which is formally defined as

$$H = \underbrace{I\ddot{\theta} + D_m\dot{\theta}}_{\text{Motor dynamics element}} + \underbrace{(M - \bar{M})\ddot{q} + D_L\dot{q} + C(q,\dot{q}) + G(q)}_{\text{Link dynamics element}} \tag{6}$$

2.2 Controller design

Define the trajectory tracking error as $e = q_d - q$, q_d is the desired angular position vector of the joints. Then, the proposed control scheme is given as

$$\tau_m = \bar{M}\left(\ddot{q}_d + K_p e + K_D\dot{e}\right) + \hat{H} \tag{7}$$

where $\hat{H}$ stands for the estimation of *H* given in Eq.(6)

Usually, $H(q,\dot{q},\ddot{q})$ is not easy to obtain using traditional methods. Therefore, TDE technique is adopted here as

$$\hat{H} = H_{(t-\eta)} = \tau_{(t-\eta)} - \bar{M}\ddot{q}_{(t-\eta)} \tag{8}$$

where $(t-\eta)$ stands for the delayed time which is often selected as several sampling period.

Combining Eq.(7) and Eq.(8), the proposed controller for the cable-driven manipulator is given as

$$\tau_m = \bar{M}\left(\ddot{q}_d + K_p e + K_D\dot{e}\right) + \tau_{(t-\eta)} - \bar{M}\ddot{q}_{(t-\eta)} \tag{9}$$

As shown in the controller Eq.(9), the dynamic model is totally not used which means Eq.(9) is model-free and easy to use in practical applications. Meanwhile, the noise effect caused by the adoption of acceleration can be suppressed with a simple low-pass filter.

2.3 Stability analysis

Substituting controller Eq.(7) into dynamic model Eq.(5), we have

$$\ddot{e} + K_D\dot{e} + K_p e = \varepsilon(t) \tag{10}$$

where $\varepsilon = -\bar{M}^{-1}\left(\hat{H} - H\right)$ is defined as the TDE error, and its boundedness prove can be found in (Jin 2009).

Equation (10) is a typical second order linear system, the boundedness of *e* can be easily ensured with properly selected K_P and K_D under the condition that ε is bound.

3. Experiment studies

To verify the effectiveness of our proposed controller for the newly design cable-driven manipulator, some experiments had been conducted.

3.1 Experiment setup

The designed cable-driven manipulator is shown in Fig.1 and the following experiment was conducted using the last joint of Fig.1. All the motors are installed in the basement instead of the joints. The controller is implemented in the *x*PC system with a NI board 6229, the sampling frequency is selected as 1kHz. And an encoder with accuracy of 0.045°was adopted. Corresponding control parameters are selected as $\eta = 0.002\text{s}, \bar{M} = 0.01, K_P = 4,\ K_d = 4$. A one order inertia filter 1/(T.s+1) with a time constant T=5ms is adopted to smooth the angular signal. Moreover, a deadband compensator 0.7sign(u) was added into the proposed controller to compensator the hard nonlinearities (Wang 2016) .

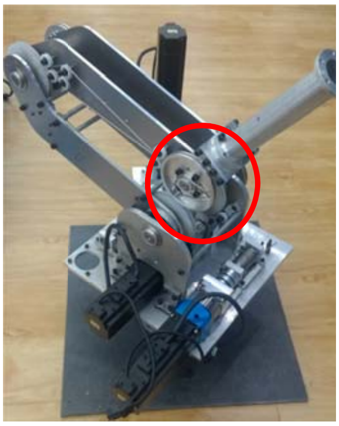

Fig. 1 The newly designed cable-driven manipulator "Polaris-I" without last 3-DOFs

3.2 Experiment results

Corresponding results are given in Fig. 2-3. To show the tendency of the control effort clearly, the deadband compensator was not given in Fig. 3 since it is just a constant.

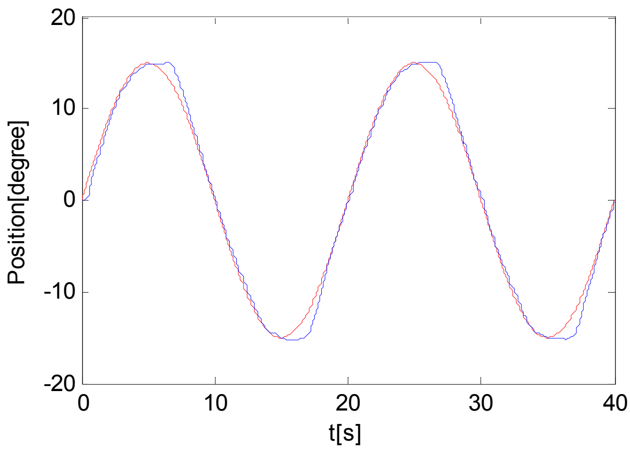

Fig. 2 Trajectory tracking performance: red solid (desired) vs blue solid (actual);

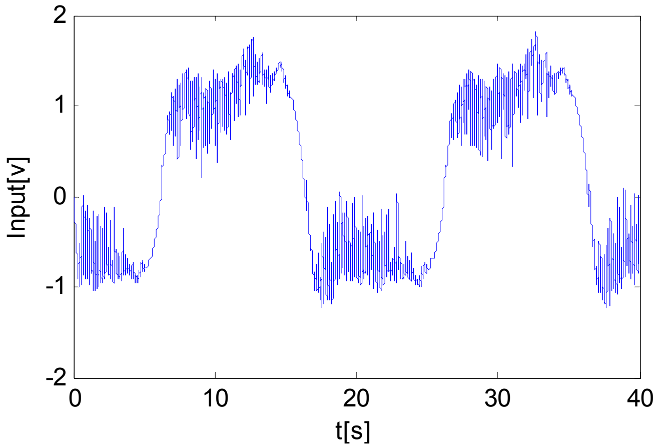

Fig. 3 Control effort without deadband compensator

As show in Fig. 2, the proposed controller can ensure relative precise trajectory tracking control performance. It is also obvious that big tracking errors appear when the manipulator moves reversely. This kind of tracking errors mainly caused by the friction and the tension changes on both side of the driven cable. Moreover, a little noisy control effort was reported in Fig. 3, which is mainly caused by the measurement noise. However, it is also clear that the noise in control effort is obvious bound.

In the future, we will combine the TDC with sliding mode control (SMC) for our newly designed cable-driven manipulator to further improve the control performance of.

4. CONCLUSIONS

A nonlinear robust control scheme using TDE technique is proposed and investigated for the control problem of our newly designed cable-driven manipulator in this work. The proposed method mainly has two parts, the TDE part and the desired dynamic part. The first one is used to estimate and compensate the lumped unknown system dynamics, which results in an attractive model-free nature. The second one is adopted to regulate the dynamic performance of the closed-loop control system. The proposed method is easy to use in practical applications thanks to TDE, and can ensure satisfactory control performance benefiting from the designed desired dynamic equation. Finally, the effectiveness of this method for our newly design cable-driven manipulator was demonstrated through an experiment.

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