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Robust tip trajectory synchronisation between assumed modes modelled two-link flexible manipulators using second-order PID terminal SMC

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HIGHLIGHTS

- The paper addresses the tip trajectory synchronisation of two identical AMM TLFMs.
- Such synchronisation is not seen in the literature.
- A second order PID terminal SMC (SO-PID-TMSC) control technique is proposed.
- The robustness of the controller is evaluated in the presence of payload variation.
- Robustness is also evaluated with the model parametric uncertainties upto ±30%.
- The performances of the controller is compared with the normal second-order SMC.
- The proposed controller is better in terms of error, low and smoother control energy.

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ABSTRACT

Synchronisation/cooperation between manipulators is a specified emerging application in the field of robotics. However, most of the synchronisation works are reported using rigid manipulators. Flexible manipulators have their advantages over rigid manipulators and hence, the applications of flexible manipulators are more desirable. This paper takes an attempt for the robust tip trajectory synchronisation between assumed modes method modelled two-link flexible manipulators. The synchronisation is achieved between a controlled master and an identical slave manipulators. A conventional SMC is designed for the tip trajectory tracking control of the master manipulator. A second order PID terminal SMC is proposed for the synchronisation between the controlled master and an identical slave manipulators along with fast suppression of tip deflection. This control technique provides chattering free global stability of the error dynamics. The structure of the proposed controller differs from the available second order terminal SMC by enabling chattering free complete stability having no singularity problem for the synchronisation of the flexible manipulators. This superiority of the proposed technique is validated using MATLAB simulation in the presence of variable payloads and ±5% to ±30% variation in the nominal value of the parameters. The effectiveness of the proposed control technique is compared with the normal second-order SMC, and is found better in terms of low tracking error and smoother control efforts.

1. Introduction

The anthropomorphic manipulators, an important part of robotics is used for moving loads in specialised jobs [1]. Due to the increasing demands of thin, lightweight and lower energy consumption in space and industries, flexible link manipulators (FLMs) are gaining technological significance over rigid manipulators [2–5]. Controlling of a FLM is challenging due to the spatially distributed states which makes the system dynamics nonminimum phase and underactuated [6]. The effective operation of serial manipulators require an accurate and coordinated control algorithms. Coordination, cooperation and synchronisation are the synonyms used to define the mutual time cooperation between the two processes [7]. However, some of the inherent disadvantages [8–10] of serial flexible manipulators limit its efficient applications. Thus, serial manipulators with coordinated flexible links are more desirable. The motivation of this paper is in designing of an appropriate

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Nomenclature

m	Notation for master manipulator.
s	Notation for slave manipulator.
y_d, y_m, y_s	Desired trajectory, trajectory of the master and slave manipulators.
s_{im}, s_{is}	Sliding surface of the ith link of the master and slave manipulators.
σ_i	SO-PID-terminal sliding surfaces for synchronisation.
q_m, q_s	States of the manipulator for master and slave.
e_{im}, e_{is}	Error of the ith link of the master and slave manipulators.
θ	Angular position of the manipulator from the generalised coordinate.
δ	Mode of the flexible manipulator.
$tip_{im}d, tip_{im}, tip_{is}(\pm n\%)$	Desired tip trajectory, tip trajectory for the ith link of the master and slave manipulators with $\pm n\%$ uncertainty.
$u_{im}(\pm n\%)$	Tip deflection for the ith link of the master manipulator with $\pm n\%$ uncertainty.
$\tau_{im}, \tau_{is}(\pm n\%)$	Required torque for the ith link of the master and slave manipulators with $\pm n\%$ uncertainty.
$Case-I/Case-A$	Synchronisation between nominal master with 0.145 kg payload and nominal slave with 0.145 kg payload.
$Case-II$	Synchronisation between a controlled master with +30% parametric uncertainties and a slave with −30% parametric uncertainties.
$Case-B$	Synchronisation between a controlled master with 0.145 kg payload and a slave with 0.3 kg payload.

control technique for the synchronisation of two-link flexible robot manipulators.

Many papers are available on the synchronisation of rigid robot manipulators [2,4,11–13]. The synchronisation of robot manipulators can be broadly divided into three categories. These are motion synchronisation [5,7,13], force synchronisation [11,13,14] and task space/trajectory synchronisation [15,16]. The synchronisation of robot manipulators are categorically explained in [7,12]. It is to be noted that most of the available synchronisation concepts are focused on the rigid manipulators which are generally not precise, economic and effective in industrial applications. Reference [17] deals with the synchronisation of self-sustained electromechanical systems with flexible arm consisting of a Rayleigh–Duffing oscillator coupled magnetically to a flexible beam. The synchronisation is between a regular and a chaotic states where the considered system has one flexible link and has two states. The synchronisation between two-link flexible manipulators (TLFM) is a new approach in industrial applications. The synchronisation between two two-link flexible manipulators is rarely available in the literature. The recent papers on manipulator synchronisation are categorised in Table 1. It is seen from Table 1 that no tip trajectory synchronisation between assumed modes modelled TLFMs are reported.

The important aspects (operation precision) of a synchronisation strategy depend on the type of control algorithms used [3,18]. Many control techniques are used for the synchronisation of rigid robot manipulators such as adaptive control [12], observer based control, feedback control [7], feedback with PD and saturated PI [19], computed torque control [20], etc. But, the performance of a control technique deteriorates when uncertainties like modelling error, backlash, friction, external disturbances [4], etc. are present. The robot manipulator dynamics is generally involved with two types of uncertainties: structured uncertainty and unstructured uncertainty [21]. The structured uncertainty includes payload variation. Sensor noise, external disturbance, friction, high frequency signal are the unstructured uncertainties [21]. Sliding mode control (SMC) techniques give better result even in the presence of such unstructured uncertainties. Generally, SMC ensures global stability and convergence of system dynamics [22–24].

Several SMC techniques are used for synchronisation of rigid manipulators like SMC with adaptive control [19], adaptive backstepping SMC [32], low pass filter based SMC [33], integral SMC [4], SMC with fuzzy logic and H_∞ [34], etc. Normally, in a conventional SMC, chattering, high gain, asymptotic stability [22] are considered as disadvantages. Nevertheless, for the first order SMC, chattering can be reduced by using saturation function in place of signum function. But, it is seen that the tracking precision and disturbance rejection property get degraded due to the boundness of sliding mode variables [22]. An integral SMC is proposed in [4] to overcome the requirement of high gain. The terminal sliding surfaces are designed to achieve the finite time stability [22,35,36]. Terminal sliding mode control (TSMC) techniques are also used for different control problems of a TLFM [37–40]. However, if the initial states of the system are far away from the equilibrium point, a good convergence performance may not be achieved by a TSMC. Another disadvantage of the first order TSMC is the singularity problem which requires a large control effort [21].

Many methods are available to reduce or to eliminate the chattering like quasi-SMC, low pass filters, fuzzy-SMC, higher order SMC (HOSMC) [21]. A HOSMC is considered as a good controller in all respect. In the case of a second-order SMC, the actual control is a continuous integration of its derivative owing to the elimination of chattering [22]. Hence, the chattering phenomena are overcome with higher order SMC or other SMC techniques [23]. The synchronisation of flexible manipulators is expected to be robust with variable payloads and external disturbances. It is to be noted that due to the sudden change in payload and external disturbances, uncertainty may occur in the system during synchronisation. Thus, it requires better (SMC) control techniques to work well under such circumstances. The reported papers on SMC techniques which are used for TLFMs only are categorised in Table 2. It is noted from Table 2 that no SO-PID-TSMC is designed for TLFMs.

In this paper, synchronisation between two assumed modes method (AMM) modelled TLFMs is presented. The synchronisation is achieved between one controlled master and one slave TLFM. A second-order PID terminal SMC (SO-PID-TSMC) control technique is proposed for the synchronisation strategy and to suppress the tip deflections. To check the robustness of the synchronisation strategy, external bounded disturbances as well as parametric uncertainties in the range of ±5%–±30% are added to the master and slave manipulators. An increase in payload of 0.155 kg is added to the slave manipulator during synchronisation. It is shown that the synchronisation of the manipulators is achieved successfully even in the presence of the said uncertainties. The main contributions and novelty of the paper as compared with the available literature are listed as:

1. The paper addresses the tip trajectory synchronisation between two identical AMM modelled TLFMs. Such synchronisation between the flexible manipulators is not found in the literature.
2. A second-order PID terminal SMC (SO-PID-TMSC) control technique is proposed for the synchronisation.
3. The robustness of the proposed control technique is evaluated in the presence of payload variation and model parametric uncertainties up to ±30% of their normal values.
4. The performances of the proposed control technique is compared with the normal second-order SMC and is found better in terms of low steady state tracking error, low and smoother control energy.