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Super-Twisting Sliding Mode Control for a Formation of Fully-Actuated Multirotor Aerial Vehicles

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Abstract: This work is concerned with the robust attitude and position control of a rigid formation of fully-actuated multirotor aerial vehicles with fixed rotors. A six-degrees-of-freedom force-torque control law is designed for each vehicle using a super-twisting sliding mode controller. The formation position and attitude commands are generated by a S-curve trajectory planner. The method is evaluated for a formation of non-planar fully-actuated hexacopter with fixed rotors and demonstrated using numerical simulations, which shows its effectiveness.

Keywords: multirotor aerial vehicle, super-twisting sliding mode control, nonlinear dynamics.

1. Introduction

Many of the applications for multirotor aerial vehicles (MAVs) seem to benefit from the use of fully-actuated vehicles since they are capable of independently maneuver in position and attitude and perform fast disturbance rejection [1]. On the other hand, the MAV mission area and effectiveness are general limited by its reduced payload capacity and flight autonomy. To overcome or mitigate these problems, it is often more effective to deploy a formation of these vehicles.

In disturbed formation flights, an accurate robust tracking performance of each vehicle is crucial to maintain a desired formation. In this sense, we design a sliding mode control (SMC) strategy for the MAVs. The conventional SMC has two phases: 1) the reaching phase, which is disturbance sensitive and 2) the sliding phase, which is disturbance insensitive. During the sliding phase, chattering appears in real systems due to time discretization and unmodeled dynamics, degrading the designed performance [2]. To diminish chattering, a super-twisting SMC is proposed for each vehicle to reject Lipschitz disturbances. The formation position and attitude reference commands are generated, using a S-curve trajectory planner. In this sense, for limited disturbances, the tracking error of each MAV is bounded in the reaching phase and the formation robustly converges to its desired pose in the sliding phase. This abstract briefly shows the MAVs dynamic modelling, the proposed controller, and the numerical results to demonstrate the effectiveness of the method.

2. Results and Discussion

Consider a formation of n fully-actuated MAVs with fixed rotors. Let $\boldsymbol{x}^i \triangleq (\boldsymbol{x}_1^i, \boldsymbol{x}_2^i) \in \mathbb{R}^{12}$ be the ith MAV vector of state errors, where $\boldsymbol{x}_1^i \in \mathbb{R}^6$ denotes the position and attitude errors and $\boldsymbol{x}_2^i \in \mathbb{R}^6$ represents the linear and angular velocities errors. Therefore, the ith MAV nonlinear dynamics is

$$\dot{\boldsymbol{x}}_1^i = \boldsymbol{f}_1(\boldsymbol{x}^i), \tag{1}$$
$$\dot{\boldsymbol{x}}_2^i = \boldsymbol{f}_2(\boldsymbol{x}^i) + \boldsymbol{B}(\boldsymbol{x}^i)(\boldsymbol{u}^i + \boldsymbol{d}^i), \tag{2}$$

where $\boldsymbol{f}_1: \mathbb{R}^{12} \to \mathbb{R}^6$, $\boldsymbol{f}_2: \mathbb{R}^{12} \to \mathbb{R}^6$, $\boldsymbol{B}: \mathbb{R}^{12} \to \mathbb{R}^{6\times 6}$ are known functions, $\boldsymbol{u}^i \in \mathbb{R}^6$ is a force-torque control command of the ith MAV, and $\boldsymbol{d}^i \in \mathbb{R}^6$ is an unknown but limited force-torque disturbance with Lipchitz derivative. Moreover $\boldsymbol{f}_1$ and $\boldsymbol{B}$ are such that $(\partial \boldsymbol{f}_1 / \partial \boldsymbol{x}_2)\boldsymbol{B}$ is non-singular. Now, let us define the ith MAV sliding variable $\boldsymbol{s}^i \triangleq \boldsymbol{f}_1(\boldsymbol{x}^i) + \boldsymbol{C}^i \boldsymbol{x}_1^i \in \mathbb{R}^6$, where $\boldsymbol{C}^i \in \mathbb{R}^{6\times 6}$ is a design diagonal matrix. Therefore, the following control law guarantees the sliding mode existence ($\boldsymbol{s}^i = \boldsymbol{0}$):

$$\boldsymbol{u}^i = -\left(\frac{\partial \boldsymbol{f}_1}{\partial \boldsymbol{x}_2}\boldsymbol{B}\right)^{-1}\left(\boldsymbol{C}^i \boldsymbol{f}_1 + \frac{\partial \boldsymbol{f}_1}{\partial \boldsymbol{x}_1}\boldsymbol{f}_1 + \frac{\partial \boldsymbol{f}_1}{\partial \boldsymbol{x}_2}\boldsymbol{f}_2 + \boldsymbol{K}_1^i \boldsymbol{\Gamma}^i \mathrm{sign}(\boldsymbol{s}^i)\right) + \boldsymbol{w}^i, \tag{4}$$

$$\dot{\boldsymbol{w}}^i = -\boldsymbol{K}_2^i \mathrm{sign}(\boldsymbol{s}^i), \tag{5}$$

where $\boldsymbol{\Gamma}^i \triangleq \mathrm{diag}\left((s_1^i)^{0.5}, \ldots, (s_6^i)^{0.5}\right)$ and $\boldsymbol{K}_1^i \in \mathbb{R}^{6\times 6}$ and $\boldsymbol{K}_2^i \in \mathbb{R}^{6\times 6}$ are diagonal matrices.

The simulation is performed for a delta formation of three non-planar fully-actuated hexacopters with fixed rotors. The formation mission is to displace (2, 10, 4) m from its initial position in 8 s. Figure 1(a) shows the formation path, the MAV size, and the formation shape at specific time instants. Each MAV is subjected to different cosine disturbances with frequency of 0.08 Hz and amplitudes of 1 N for force and 0.2 Nm for torque. Figure 1(b) shows the norm of the relative position between MAV 1 and MAVs 2 and 3, denoted, respectively, by $\vec{r}^{1/2}$ and $\vec{r}^{1/3}$. Figure 1(c) shows the position tracking performance of MAV 1.

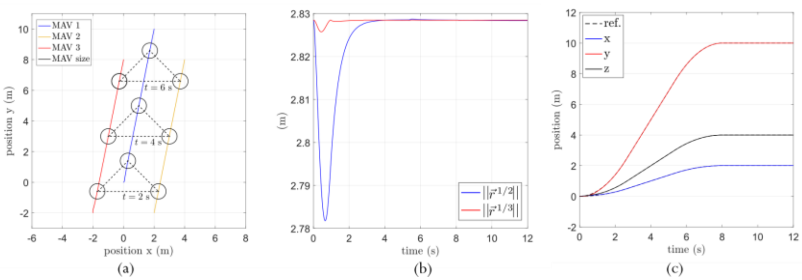

Fig. 1: (a) Formation path, MAV size, and formation shape at time instants 2 s, 4 s, and 6 s. (b) relative distance between MAV 1 and MAVs 2 and 3. (c) position tracking performance of MAV 1.

3. Concluding Remarks

This paper has presented the design of a super-twisting SMC for a formation of fully-actuated MAVs with fixed rotors. A simulation example showed that the proposed super-twisting SMC generates negligible chattering and robustly attains the desired formation pose after a finite time.

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