

Adaptive robust nonsingular terminal sliding mode design controller for quadrotor aerial manipulator

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Abstract

In this paper, a novel adaptive control approach for Unmanned Aerial Manipulators (UAMs) is proposed. The UAMs are a new configuration of the Unmanned Aerial Vehicles (UAVs) which are characterized by several inherent nonlinearities, uncertainties and coupling. The studied UAM is a Quadrotor endowed with two degrees of freedom robotic arm. The main objectives of our contribution are to achieve both a tracking error convergence by avoiding any singularity problem and also the chattering amplitude attenuation in the presence of perturbations. Therefore, the proposed Adaptive Nonsingular Terminal Super-Twisting controller (ANTSTW) consists of the hybridization of a Nonsingular Terminal Sliding Mode Control and an Adaptive Super Twisting. The adaptive law, which adjust the Super-Twisting's parameters, is obtained by using stability Lyapunov theorem. Simulation experiments in trajectory tracking mode were realized and compared with Nonsingular Terminal Super-twisting control to prove the superiority and the effectiveness of the proposed approach.

Keywords: adaptive law, lyapunov theorem, super-twisting, terminal sliding mode, unmanned aerial manipulator (UAM)

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1. Introduction

In the few last years, Unmanned Aerial Manipulators (UAMs) appeared as a new research area in the field of robotic and automation. The main potential of the UAMs is their capability to interact safely with the environment and perform complex tasks at locations known to be inaccessible to humans. Several UAM systems have been realized and deployed such as helicopters with a highly compliant gripper [1], the stabilization of the system when lifting a grasped object and transporting it in free flight is also presented in [1]. Quadrotor equipped with manipulator has been designed, modeled and controlled in [2, 3]. In [4] a small Quadrotor with several types of grippers has been designed and the ability to grasp and manipulate a number of items is tested. UAM system with dual arms has been proposed and used to valve actuating in [5]. Furthermore, a group of Quadrotors is employed for lifting large objects using similar gripper, which their design is detailed in [6].

On other hand, from automatic viewpoint, Quadrotors and robotic manipulators are complex dynamic systems where many control approaches have been proposed [7-11]. Quadri-manipulator combined system dynamics is more complex with several inherent nonlinearities, coupling, structured and unstructured uncertainties, under-actuation, etc. These difficulties make controlling such systems a hard challenge to overcome. Some control approaches have been proposed; in [12] a model-based controller for a small-scaled helicopter equipped with a robotic arm has been proposed. Reference [13] presents a Lyapunov based model reference adaptive control combined with gain scheduling for multi-arm implemented on a small Quadrotor. Cartesian impedance control approach with exploiting redundancy has also been proposed, simulated and tested in [14, 15]. Null space based behavioral framework has been adopted in [16]; feedback control strategy [17] and adaptive sliding mode control [18] are also proposed to avoid the destabilization effects caused by the manipulator movements. The reader is referred [19] to provide a literature review and details achievements on aerial manipulation.

Sliding Mode Control (SMC) appears to be a promising solution to deal with model uncertainties because it has well known perturbations rejection properties. It has attracted the interest of the control community in different fields [8, 20-22] due to its capability to reject the disturbance, invariance property, order reduction, simplicity of design and implementation. Nonsingular Terminal Sliding-Mode-Control (NTSMC) is a particular case of SMC, which is relatively new method. NTSMC is able to provide a finite time convergence with good accuracy by using nonlinear surface [23]. However, it still suffers from chattering drawback; it shows undesirable oscillation on the system, leads to low control accuracy, causes high wear of the moving mechanical parts, and may damage the actuators. Some solutions have been proposed to avoid this handicap such as the modification of the discontinuous control part and the use of High Order SMC [21, 24, 25]. From the best of our knowledge, few works have used the SMC for controlling UAV systems with manipulator. Authors in [18] have presented an adaptive sliding mode controller for a Quadrotor with robotic arm; the efficacy of this controller has been tested in flight experiments. Earlier, they have used an adaptive controller based on sliding mode approach in trajectory tracking mode for a Hexacopter with two degree of freedom robotic arm [26]. However, the use of linear sliding surface leads usually to an asymptotic convergence.

To resolve this problem and as a contribution to Aerial Manipulator control issue, a robust adaptive sliding mode strategy has been proposed by using a high order-sliding mode with nonlinear surface for Quadrotor endowed with two degrees of freedom robotic arm. In such complex and under-actuated system, the design of a robust control is naturally required to compensate the intrinsic and the extrinsic uncertainties, measurement errors and unmolded dynamics. The proposed control strategy called Adaptive Nonsingular Terminal Super-Twisting (ANTSTW) combines the efficiency of both NTSMC and Adaptive Super-Twisting Algorithm (ASTW). The major objective of this paper is to extend the works presented in [27, 28] by using a new terminal sliding variable to avoid any singularity problem and achieve fast finite time convergence. Furthermore, this proposed combined approach improves performances and guarantees the robustness in presence of perturbations with minimal chattering effects. This schemes of design, not only ensure that the system states arrive at the equilibrium point in a finite time but also offer some attractive properties, such as their fast response and higher precision. Stability of the UAM in closed loop is proved using the classical Lyapunov criterion. Simulation experiments are performed in trajectory tracking mode and compared with the NTSTW controller in both: free moving and using a payload. This paper is organized as follow: in section 2, the dynamic model of the whole system is developed. The proposed ANTSTW design and stability analyses are detailed in section 3. Section 4 presents simulation results, and finally a conclusion is given in section 5.

2. Dynamic UAM modeling

Consider an UAM composed by Quadrotor equipped with 2-DOF robotic arm as shown in Figure 1. The references frames shown in Figure 1 are defined as follow:

Σ_i : is the world inertial reference frame.

Σ_b : is the body frame placed at the Quadrotor center of mass.

Σ_{l_i} : is the body-fixed frame placed at the center of mass of the link i . The generalized coordinate variables are given the vector:

$$\xi = \begin{bmatrix} p_b^T & \phi_b^T & \eta^T \end{bmatrix} \quad (1)$$

Where,

$p_b = [x \ y \ z]^T$: is the absolute position of the UAM with respect to Σ_i .

$\phi_b = [\varphi \ \theta \ \psi]^T$: is the UAM attitude, it is defined by Euler Angles

$\eta = [\eta_1 \ \eta_2]^T$: is the vector of joint manipulator angles.

The dynamic model of the UAM system has the standard form of the dynamic robotic systems which can be obtained by using the Euler-Lagrange formulation [29, 30]:

$$B(\xi)\ddot{\xi} + C(\xi, \dot{\xi})\dot{\xi} + G(\xi) = U + U_{ext} \quad (2)$$

Where,

B : is the (8×8) Inertia matrix which is symmetric positive, its elements are given in [14].

C : is the (8×8) Coriolis and Centrifugal forces matrix, its elements are given by:

$$c_{ij} = \sum_{k=1}^8 \frac{1}{2} \left(\frac{\partial b_{ij}}{\partial \xi_k} + \frac{\partial b_{ik}}{\partial \xi_j} + \frac{\partial b_{jk}}{\partial \xi_i} \right) \dot{\xi}_k, \quad b_{ij} : \text{Elements of } B$$

G : is the gravity forces vector, its elements are given as: $G_{(8 \times 1)} = \left(\frac{\partial u(\xi)}{\partial \xi} \right)^T$, $u(\xi)$: potential energy.

U : is the generalized input forces vector, it is given as: $U_{(8 \times 1)} = \bar{R}_b N f$ Where: $\bar{R}_b_{(8 \times 8)}$

$N_{(8 \times 6)}$ are detailed in [14], $f = \begin{bmatrix} f_v^T & \tau^T \end{bmatrix}$, $f_v = [u_1 \ u_2 \ u_3 \ u_4]$ is the vector of forces given by the Quadrotor motors, $\tau = [\tau_1 \ \tau_2]$ The input vector of manipulator actuation torques.

U_{ext} : (8×1) is the external generalized forces vector.

$\dot{\xi} = \begin{bmatrix} \dot{p}_b^T & \dot{\phi}_b^T & \dot{\eta}^T \end{bmatrix}$ and $\ddot{\xi} = \begin{bmatrix} \ddot{p}_b^T & \ddot{\phi}_b^T & \ddot{\eta}^T \end{bmatrix}$ are the velocities and accelerations vectors, respectively.

Namely, we can transform the dynamic model of the UAM given by (2) into the following equation:

$$\ddot{\xi} = B^{-1}(-C\dot{\xi} - G + U) \quad (3)$$

Assumption 1 for the model represented by (3) we make the following assumptions:

- We consider low speed displacements.
- The aerodynamic effects are negligible therefore we set $U_{ext} = 0$.

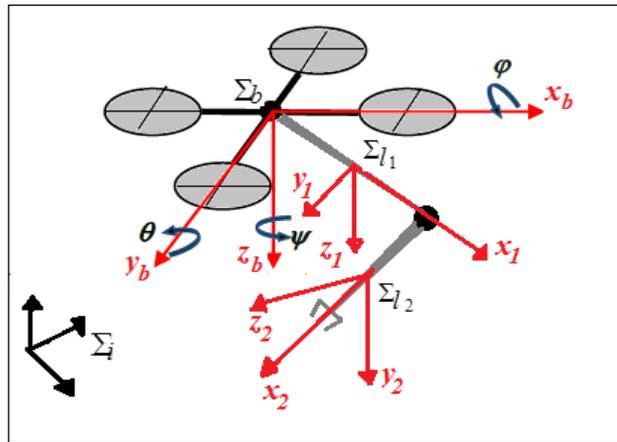


Figure 1. UAM system with the correspondence references frames

3. Control Design

The NTSMC ensures the finite-time convergence of the variables states; this control method is based on a nonlinear sliding variable defined as follow [23]:

$$S = e + W e^{\rho} \quad (4)$$

Where, $S = [s_1, \dots, s_8]^T$, $e = \xi - \xi_d$, $\dot{e} = \dot{\xi} - \dot{\xi}_d$ with ξ_d and $\dot{\xi}_d$ are the desired trajectory vectors and their times derivatives respectively, $W = \text{diag}(w_i), w_i > 0$ for $(i = 1 \text{ to } 8)$ and e^{ρ} is denoted as: $e^{\rho} = [e_1^{\rho_1}, \dots, e_8^{\rho_8}]^T$, $1 < \rho_i = \frac{p_i}{q_i} < 2$ with p_i and q_i are constants odd integers. In expression (4), for $\dot{e} < 0$ the term e^{ρ} may be not real because of the fractional power ρ , which leads $S \notin R$. To avoid this problem, we use a new form of NTS variable, which was proposed in [27, 28]:

$$S = e + W |\dot{e}|^{\rho} \text{sign}(\dot{e}) \quad (5)$$

Where, $|\dot{e}|^{\rho} \text{sign}(\dot{e}) = [|\dot{e}_1|^{\rho_1} \text{sign}(\dot{e}_1), \dots, |\dot{e}_8|^{\rho_8} \text{sign}(\dot{e}_8)]^T$. Substituting the (3) in ($\dot{S} = 0$), we can extract the equivalent control as:

$$U_{eq} = C \dot{\xi} + G - B \left(\Lambda^{-1} W^{-1} |\dot{e}|^{(2-\rho)} \text{sign}(\dot{e}) - \ddot{\xi}_d \right) \quad (6)$$

Where, $\Lambda = \text{diag}(\rho_i)$ for $(i = 1 \text{ to } 8)$. Therefore, we can write the NTSMC with the discontinuous control as:

$$U = C \dot{\xi} + G - B \left(\Lambda^{-1} W^{-1} |\dot{e}|^{(2-\rho)} \text{sign}(\dot{e}) - \ddot{\xi}_d - U_{dis} \right) \quad (7)$$

$$U_{dis} = -\beta |S|^{1/2} \text{sign}(S) - \alpha \int_0^t \text{sign}(S) \quad (8)$$

Where, $\beta = \text{diag}(\beta_i)$ and $\alpha = \text{diag}(\alpha_i)$, $(i = 1 \text{ to } 8)$ are diagonal matrices. Substituting (8) in the control law (7), we obtain a Nonsingular Terminal Super-Twisting controller (NTSTW) given by:

$$U = C \dot{\xi} + G - B \left(\Lambda^{-1} W^{-1} |\dot{e}|^{(2-\rho)} \text{sign}(\dot{e}) - \ddot{\xi}_d + \beta |S|^{1/2} \text{sign}(S) + \alpha \int_0^t \text{sign}(S) \right) \quad (9)$$

Assumption 2 the sliding variable s is assumed to admits a relative degree equal to one with respect to u , one gets:

$$\dot{s} = \Psi(\cdot) + \Gamma(\cdot) \cdot u \quad (10)$$

functions $\Psi(\cdot), \Gamma(\cdot)$ are assumed to be such that: $0 < K_m < \Gamma(\cdot) \leq K_M$, $|\Psi(\cdot)| \leq C_0$ with: $K_m \in R^{+*}$, $K_M \in R^{+*}$, $C_0 \in R^+$, taking the time derivate of (5):

$$\dot{S} = \dot{e} + W \Lambda \text{diag}(|\dot{e}_i|^{\rho_i-1}) \cdot \ddot{e} = \dot{e} + W \Lambda \text{diag}(|\dot{e}_i|^{\rho_i-1}) (\ddot{\xi} - \ddot{\xi}_d) \quad (11)$$

the combination of (11), (3) and (9) yield:

$$\dot{S} = W \Lambda \text{diag}(|\dot{e}_i|^{\rho_i-1}) \left(-\beta |S|^{1/2} \text{sign}(S) - \alpha \int_0^t \text{sign}(S) \right) \quad (12)$$

in (12) can be written in scalar form $(i = 1, \dots, 8)$ as:

$$\dot{s}_i = w_i \rho_i |\dot{e}_i|^{(\rho_i-1)} \left(-\beta_i |S_i|^{1/2} \text{sign}(S_i) - \alpha_i \int_0^t \text{sign}(S_i) \right) \tag{13}$$

using assumption 2, we have $w_i \rho_i |\dot{e}_i|^{(\rho_i-1)} \leq K_{Mi}$, So, we can write:

$$\dot{s}_i \leq K_{Mi} \left(-\beta_i |S_i|^{1/2} \text{sign}(s_i) - \alpha_i \int_0^t \text{sign}(s_i) \right) \tag{14}$$

setting $z_{1i} = s_i$, ($i = 1$ to 8) yields:

$$\begin{aligned} \dot{z}_{1i} &= -K_{Mi} \beta_i |z_{1i}|^{1/2} \text{sign}(z_{1i}) + z_{2i} \\ \dot{z}_{2i} &= -K_{Mi} \alpha_i \text{sign}(z_{1i}) + \mathcal{G}_i(z_i, t) \end{aligned} \tag{15}$$

where the perturbation term \mathcal{G}_i is bounded $|\mathcal{G}_i| \leq \sigma_i$, σ_i is positive constant. The ANTSTW controller structure is shown in Figure 2.

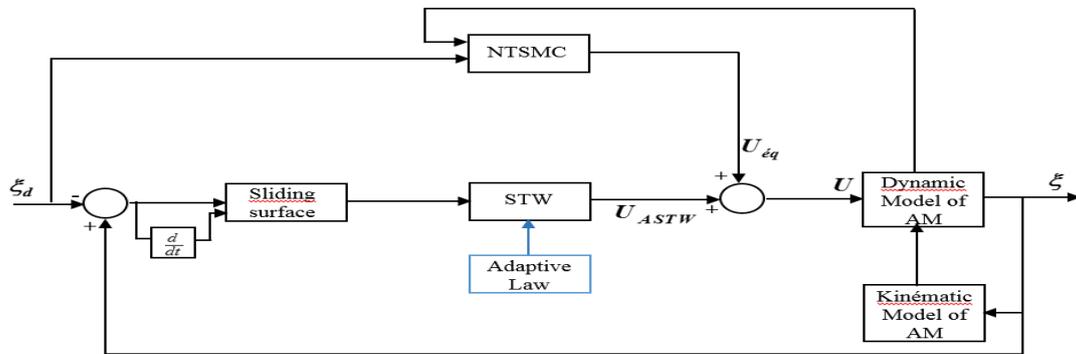


Figure 2. ANTSTW control scheme

In order to improve the performances and counteract the uncertainties, we adjust the gains of STW (β, α) via the following theorem. THEOREM 1. Consider the dynamics robotic system given by (3), and using the NTS variable (5), the Adaptive Super-Twisting Nonsingular Terminal Sliding-Mode-Controller (ANTSTW) is given by:

$$U = C \dot{\xi} + G - B \left(\Lambda^{-1} W^{-1} |\dot{e}|^{(2-\rho)} \text{sign}(\dot{e}) - \ddot{\xi}_d + \beta |S|^{1/2} \text{sign}(S) + \alpha \int_0^t \text{sign}(S) \right) \tag{16}$$

Where, $\beta = \text{diag}(\beta_i)$ and $\alpha = \text{diag}(\alpha_i)$, ($i = 1$ to 8) are diagonal matrices with β_i, α_i are chosen as follows:

$$\beta_i > 0, \quad \alpha_i > \frac{6\sigma_i + 4 \left(\frac{\sigma_i}{K_{Mi} \beta_i} \right)^2}{2K_{Mi}} \tag{17}$$

With, adaptive law:

$$\dot{\beta}_i(t) = \begin{cases} \omega_{1i} \sqrt{\frac{\delta_{1i}}{2}} & \text{if } (s_i \neq 0) \\ 0 & \text{if } (s_i = 0) \end{cases} \tag{18}$$

$$\dot{\alpha}_i(t) = \begin{cases} \omega_{2i} \sqrt{\frac{\delta_{2i}}{2}} & \text{if } (s_i \neq 0) \\ 0 & \text{if } (s_i = 0) \end{cases}$$

Where, $\omega_{1i}, \delta_{1i}, \omega_{2i}, \delta_{2i}$ are positive constants, then the NTS manifold (5) will be reached in finite time. Proof, let us choose the candidate Lyapunov function V_0 in quadratic form:

$$V_0(x) = Z^T P Z \quad (19)$$

Where, $Z^T = \left[|z_{1i}|^{\frac{1}{2}} \text{sign}(z_{1i}), z_{2i} \right]$ $P = \frac{1}{2} \begin{bmatrix} 4K_{Mi}\alpha_i + K_{Mi}^2\beta_i^2 & -K_{Mi}\beta_i \\ -K_{Mi}\beta_i & 2 \end{bmatrix}$. Denote, $\|Z\|_2^2 = |z_{1i}| + z_{2i}^2$,

It follows that [31]:

$$\begin{cases} \lambda_{\min}\{P\} \|Z\|_2^2 \leq V_0(z) \leq \lambda_{\max}\{P\} \|Z\|_2^2 \\ |z_{1i}|^{1/2} \leq \|Z\|_2 \leq \frac{V_0^{1/2}(z)}{\lambda_{\min}^{1/2}\{P\}} \end{cases} \quad (20)$$

differentiating (19) with respect to time gives

$$\dot{V}_0 = -\frac{1}{|z_{1i}|^{1/2}} Z^T Q Z = -\frac{1}{|z_{1i}|^{1/2}} \lambda_{\min}\{Q\} \|Z\|_2^2 \quad (21)$$

$$\text{Where, } Q = \frac{K_{Mi}\beta_i}{2} \begin{bmatrix} 2K_{Mi}\alpha_i + K_{Mi}^2\beta_i^2 - 2\sigma_i & -\left(K_{Mi}\beta_i + \frac{2\sigma_i}{K_{Mi}\beta_i}\right) \\ -\left(K_{Mi}\beta_i + \frac{2\sigma_i}{K_{Mi}\beta_i}\right) & 1 \end{bmatrix}$$

\dot{V}_0 is negative if Q is positive definite matrix which is the case if the gains verified by (17) hold. Using (20), (21), we get:

$$\dot{V}_0 \leq -r V_0^{1/2} \quad (22)$$

With, $r = \frac{\lambda_{\min}^{1/2}\{P\} \lambda_{\min}\{Q\}}{\lambda_{\max}\{P\}}$. Let us define the following Lyapunov function:

$$V = V_0 + \frac{1}{2\delta_{1i}} (\beta_i - \beta_i^*)^2 + \frac{1}{2\delta_{2i}} (\alpha_i - \alpha_i^*)^2 \quad (23)$$

Differentiating (23) with respect to time gives

$$\dot{V} \leq -r V_0^{1/2} + \frac{1}{\delta_{1i}} (\beta_i - \beta_i^*) \dot{\beta}_i + \frac{1}{\delta_{2i}} (\alpha_i - \alpha_i^*) \dot{\alpha}_i \quad (24)$$

By the addition and the subtraction of the terms $\frac{\omega_{1i}}{\sqrt{2\delta_{1i}}} |\beta_i - \beta_i^*|$ and $\frac{\omega_{2i}}{\sqrt{2\delta_{2i}}} |\alpha_i - \alpha_i^*|$ in (24), it yields:

$$\begin{aligned} \dot{V} \leq & -rV_0^{1/2} + \frac{1}{\delta_{1i}} (\beta_i - \beta_i^*) \dot{\beta}_i - \frac{\omega_{1i}}{\sqrt{2\delta_{1i}}} |\beta_i - \beta_i^*| + \frac{1}{\delta_{2i}} (\alpha_i - \alpha_i^*) \dot{\alpha}_i - \frac{\omega_{2i}}{\sqrt{2\delta_{2i}}} |\alpha_i - \alpha_i^*| \\ & + \frac{\omega_{1i}}{\sqrt{2\delta_{1i}}} |\beta_i - \beta_i^*| + \frac{\omega_{2i}}{\sqrt{2\delta_{2i}}} |\alpha_i - \alpha_i^*| \end{aligned} \quad (25)$$

we assume that the adaptation laws (18) makes the gains β_i, α_i bounded i.e. there exist positive constants such that $\alpha_i(t) - \alpha_i^* < 0$ and $\beta_i(t) - \beta_i^* < 0, \forall t > 0$ [32]. If we choose $\dot{\beta}_i$ and $\dot{\alpha}_i$ as (18) we can write:

$$\dot{V} \leq -rV_0^{1/2} - \frac{\omega_{1i}}{\sqrt{2\delta_{1i}}} |\beta_i - \beta_i^*| - \frac{\omega_{2i}}{\sqrt{2\delta_{2i}}} |\alpha_i - \alpha_i^*| \quad (26)$$

using the well-known inequality $(x^2 + y^2 + z^2)^{1/2} \leq |x| + |y| + |z|$, and in view of (23), we can rewrite (26) as:

$$\dot{V} \leq -rV_0^{1/2} - \omega_{1i} \frac{|\beta_i - \beta_i^*|}{\sqrt{2\delta_{1i}}} - \omega_{2i} \frac{|\alpha_i - \alpha_i^*|}{\sqrt{2\delta_{2i}}} \leq -KV^{1/2} \quad (27)$$

choosing $K = \min\{r, \omega_{1i}, \omega_{2i}\}$, a finite time convergence is guaranteed.

4. Simulation Results

In this section, we examine the efficacy of the proposed control approach via simulations in free moving and using payload (robustness test). Simulation tests have been carried out under the UAM which is Quadrotor with 2-DOF robotic arm. Parameters of the UAM are adopted from [14]. Simulations have been realized using MATLAB© environment in tracking trajectory mode. They are run for 60 seconds with sample time equal to 10ms. Two controllers are tested the NTSTW given by (9) and the ANTSTW given by (16) and (18). ANTSTW is presented by red lines, NTSTW is presented by green lines and the reference takes blue lines. The common surface parameters of the two controllers are: $w = \text{diag}(2, 2, 6, 0.9, 0.9, 3, 3, 4)$ $q = (9, 9, 7, 9, 9, 9, 9, 9)$, $p_i = 11$. The parameters of NTSTW controller are: $\alpha = \text{diag}(2, 2, 2, 2, 2, 3, 4, 12)$ $\beta = \text{diag}(0.1, 0.1, 0.1, 0.3, 0.3, 0.3, 4, 4)$. On other hand, the parameters of ANTSTW controller are: $\delta_1 = (0.1, 0.1, 1.5, 1.1, 1, 70, 15)$, $\delta_2 = (0.1, 0.1, 1, 0.1, 0.1, 1, 10, 2)$, $\omega_{1i} = 0.01$ $\omega_{2i} = 0.01$.

4.1. Simulation in Trajectory Tracking Mode

The initial linear and angular positions of the Quadrotor and the manipulator joints are equal to zero. The trajectory should be tracked consists of phases summarized as:

1/ In the first phase, the vertical displacement is from 0 to 4m through z , in this case $\eta_{1d} = \eta_{2d} = 0$ and x, y should follow the paths given by: $x_d = 0.5 \cdot \cos(0.5 \cdot t)$, $y_d = 0.5 \cdot \sin(0.5 \cdot t)$

2/ In the second phase $(x_d, y_d, z_d) = (0.2, 0.4576, 4)$ m and the two joints of the manipulator η_1, η_2 should follow the path given by $\eta_{1d} = \eta_{2d} = 1.05 - (7/5)e^{-(t-40)} + (7/20)e^{-4(t-40)}$.

Figure 3 shows that the best tracking of position is given by ANTSTW with high precision at $t=40$ s which corresponding to path changes of the system. One can easily see from Figure 4 that the chattering effects are attenuated significantly in the case of adaptive controller which is very useful in this application. The peaks appeared are due to the UAM inertia caused by its behaviors changes. Also, the convergence of the tracking errors is guaranteed in finite time without any singularity problem.

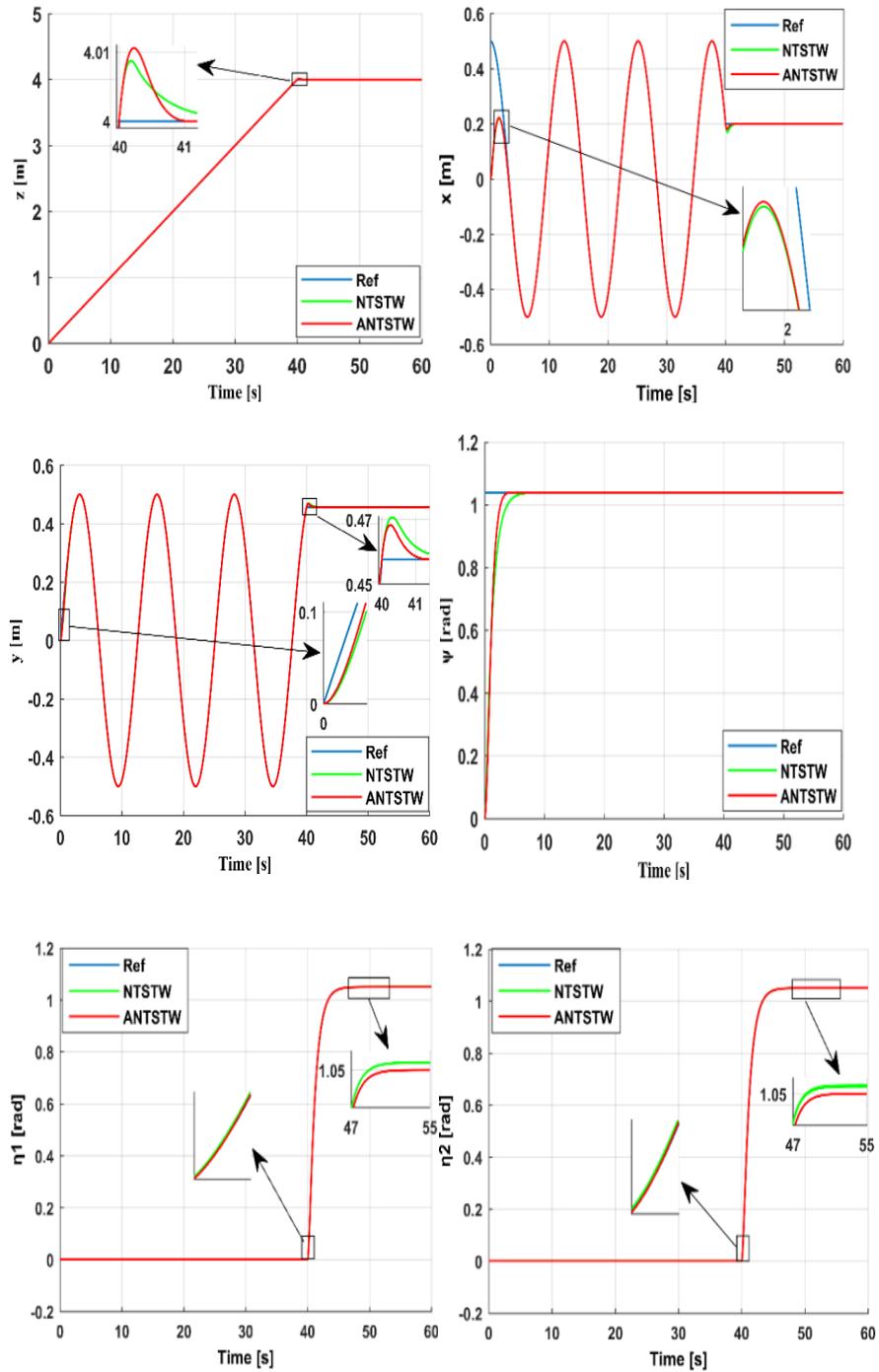


Figure 3. Application of ANTSTW and NTSTW to all joints

4.2. Robustness Tests

To examine the controllers robustness, permanent perturbation such as a mass load is attached to the link 2 of the manipulator at time $t=50s$. We maintain the same trajectories tested without any load, the used mass is equal to 0.025kg. It can be seen from Figure 5 and Figure 6. that the ANTSTW controller presents better transient performances and can overcome this uncertainty with minimal chattering effects compared with the NTSTW, this is due to the adaptation of the STW parameters via Lyapunov analysis.

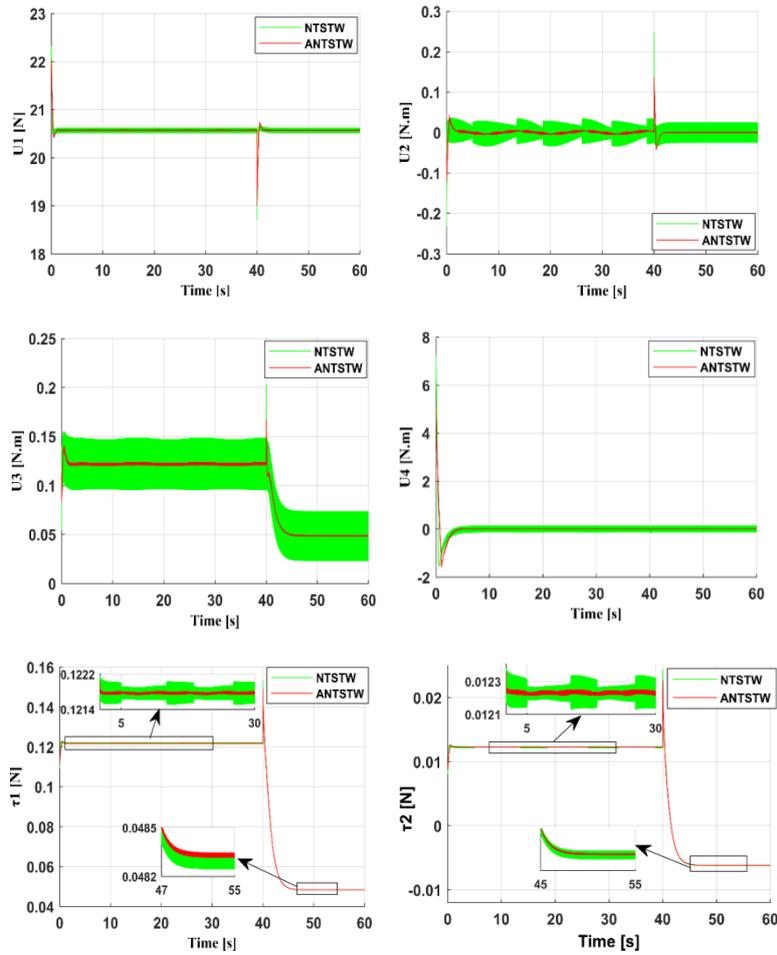


Figure 4. Application of ANTSTW and NTSTW to all joints

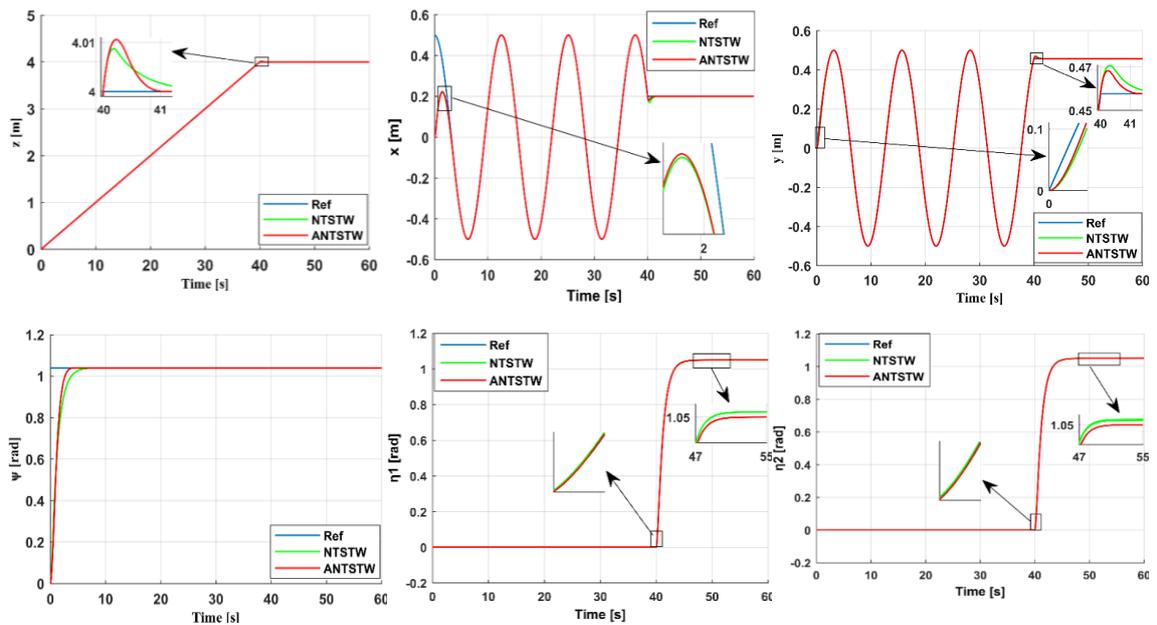


Figure 5. Robustness test of the mass load for the application of ANTSTW and NTSTW

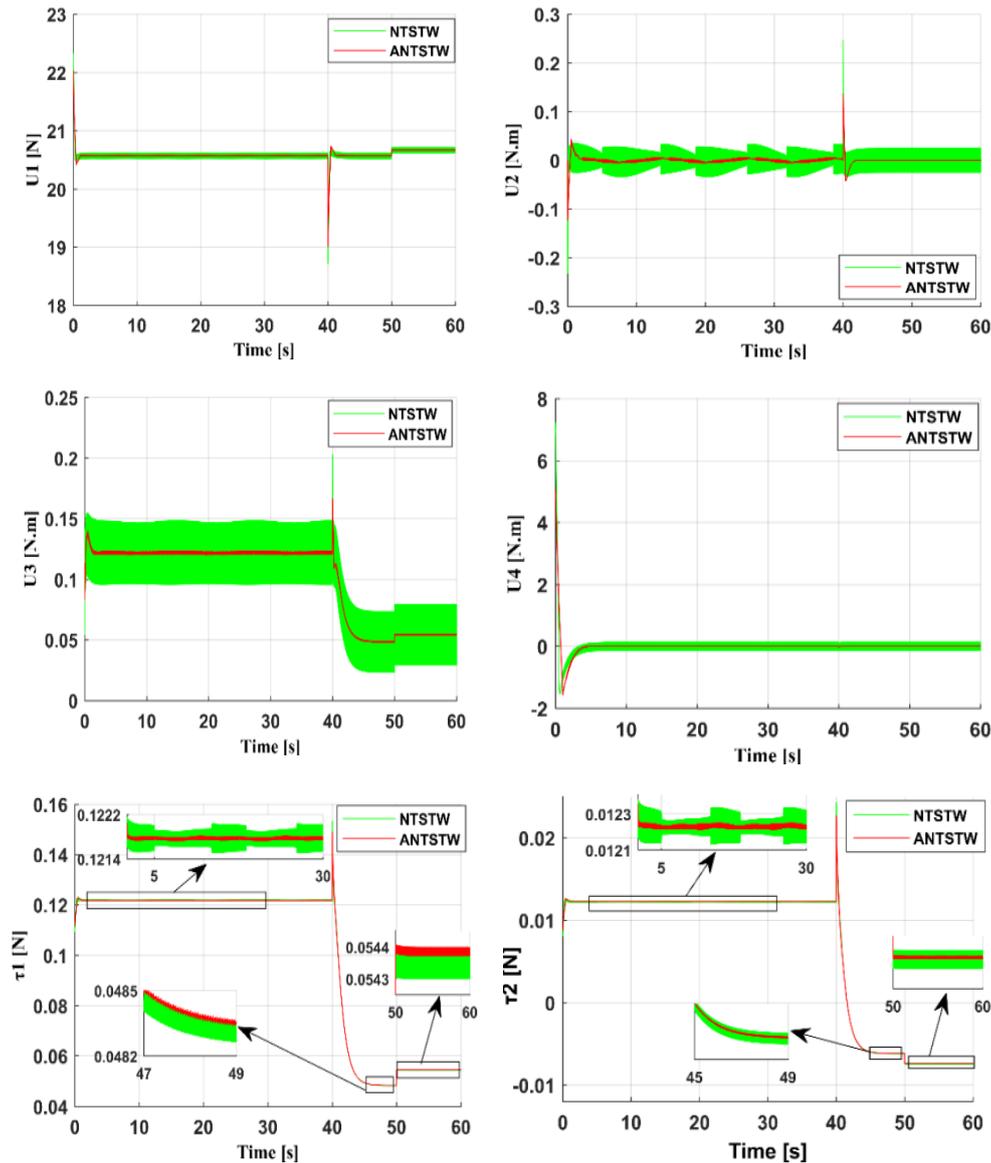


Figure 6. Control Signals of the Application of ANTSTW and NTSTW in presence of mass load

5. Conclusion

In this paper, we have proposed a novel adaptive and robust control approach for an Unmanned Aerial Manipulator which is a Quadrotor endowed by 2-DOF robotic manipulator. The control law consists of hybridization of Nonsingular Terminal Sliding-Mode-Control and Super-Twisting controller. Parameters of this last are adjusted using an adaptive law based on Lyapunov analysis; the global finite time stability of the closed-loop system is proven. The proposed control strategy combines the efficiency of both NTSMC and Adaptive Super Twisting Algorithm (ASTW); so as a result, the convergence of the tracking errors is guaranteed with minimal chattering effects without any singularity problem. Simulation results have shown that the proposed approach performs best tracking performances and guarantee robustness with respect to modelling errors and in presence of perturbations compared with NTSMC.

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