Meta-heuristic Optimization of Sliding Mode Control - Application to Quadrotor-based Inspection of Solar Panels

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Abstract.
In this paper, inspection of solar energy system is addressed using a quadrotor Unmanned Aerial Vehicle (UAV) system. The accrate positioning of the system on the solar panelrequires a robust controller to precisely address the fault while ensuring stability. For this purpose, an Optimized Nonsingular Terminal Sliding Mode Controller (ONTSMC) is proposed. The control law is designed based on the derived quadrotor model. Particule swarm optimization (PSO) method is used to optimize the controller parameters. Also, the closed-loop stability of the controller is ensured using Lyapunov candidate function. The proposed optimized controller is simulated in MATLAB/Simulink to characterize the control performance. results demonstrate the effectiveness of the proposed control approach.

Key words. **Renewable energy, Solar panels, quadrotor, terminal sliding mode, particule swarm optimization.**

1. Introduction

Renewable energy is considered as a clean energy that has become an essential source to preserve the nature. Sahara of Algeria is a vast source to produce solar energy without limit. In order to appropriate get benefits from this energy, significant investments and technological improvements are required.. Also, solar panel systems require the preservation, maintenance and inspection. Scientific literature reports several works applying robotics in renewable energy sector [1-2].

Mini Unamanned Aerial Vehicles (UAV) are avionics systems widely used, in recent years, for prevention and surveillance purposes thanks to their excellent maneuverability low cost. This work proposes the use the UAV for the inspection of defects as well as the monitoring of solar panels in a production station. A quadrator type UAV is the most commonly used configuration [3-4]. The system has a small-size and light-weight structure that is actuated by four motors to permit a vertical take-off and landing without the need to have a runway. From autonomous perspective, a quadrotor is a multivariable nonlinear system having strongly coupled dynamics and thus offers a great challenge from control point of view.

Solar panels have some technical anomalies such as; (1) Defects arising due to internal corrosion or external effects, (2) presence of the sand (3) Birds can nest beneath the panels and this may deteriorate the system performance . The problem becomes more challenging in case of big panels solar fields, where it becomes very hard to ensure all- time optimal functionality of the panels thus calling for an autonomous solution. The precision is important here to focus on the defective parts within the solar panels. Several control laws have been proposed for controlling the quadrotor trajectory with different objectives. Nonsingular Sliding Mode Control (NTSMC) offers some superior properties compared to the classic sliding mode controllers such as, finite-time response and high-precision in control and provides speed of convergence near the equilibrium point. A control approach based on NTSMC is proposed in the present research. The controller is based on a nonlinear surface which offers the desired accurate and precise trajectory. Despite several advantages of NTSMC, the singularity of this control method needs to be overcome. Several indirect approaches have been proposed in the literature to address this singularity problem. Yu et *al*. have proposed a NTSMC to address this problem [5]. Other related work have been reported in [5-6]. In order to avoid the difficulties in obtaining an accurate quadrotor model, discontinuous control part of the NTSMC deal with the modelling errors. Also, parameter optimization based on Particle Swarm Optimization (PSO) has also been proposed in [3].

The remaining of the paper is organized as follows: Section 2 presents problem statement and quadrotor system model. In Section 3 , NTSMC law for the quadrotor trajectory tracking is designed while PSO metaheuristic optimization of the controller's parameters is detailed in Section 4 . Simulation results of the optimization and trajectory tracking control are given in Section 5. Finally Section 6 concludes the paper.

2. Problem Statement and Quadrotor System Modelling

Thi the overallplatform of surveillance and maintenance of solar energy station is described. Then, description and modelling of the quadrotor system is considered.

2.1. ***Problem statement and proposed solution***: The primary objective is to design an application based on quadrotors for inspecting using cameras to address the aforementioned anomalies of solar panels The control of a quadrotor to precisely position it on the panel solar is in an interesting challenge due to the nonlinear system dynamics and other nonlinearities of the operational environment. In this work, we have designed a robust controller based on NTSMC with meta-heuristic optimization of its parameters using PSO algorithm.

2.2. ***System description and quadrotor modelling:*** The system is composed of three main parts (Fig. 1); a quadrotor, a control station, panels solar field and quadrotor systems. The quadrotors are equipped with camera used to observe the solar panels. The control station is responsible of sending control commands to the quadrotor and receiving data. through a Wi-Fi communication.

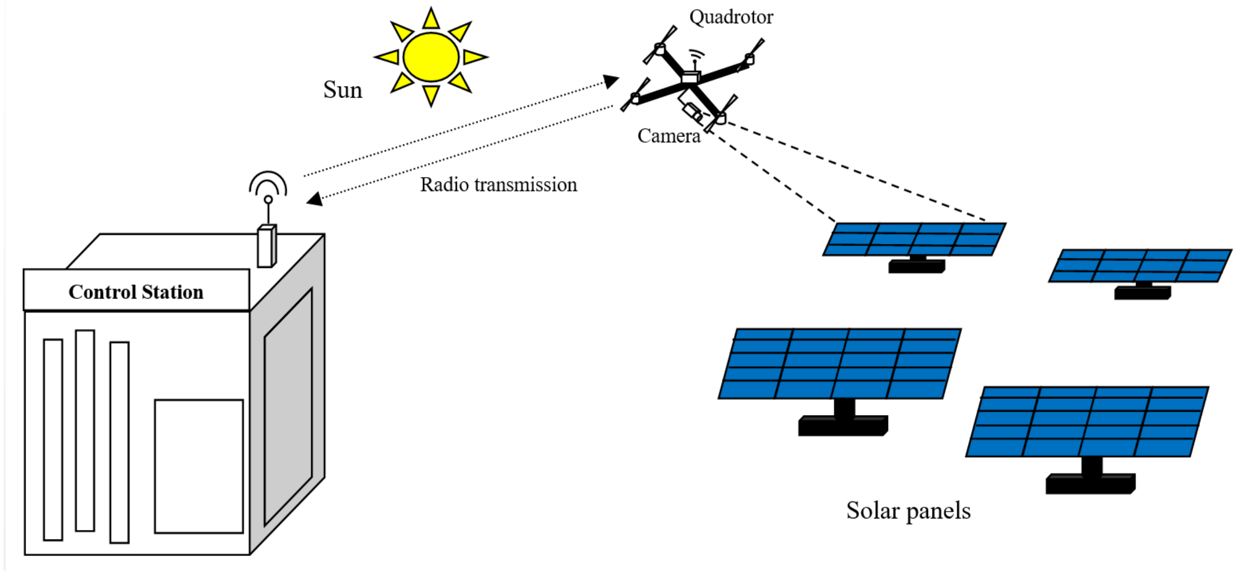

Figure.1. Quadrotor station for solar panels surveillance and maintenance

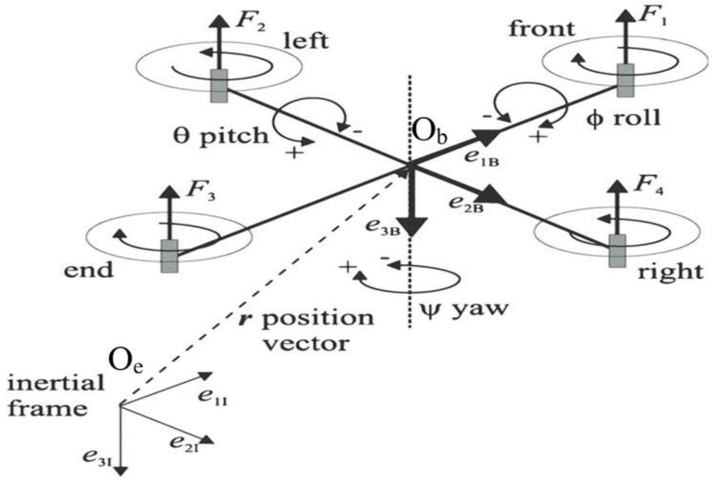

Figure.2. Schema of Quadrotor UAV

The dynamic model of a quadrotor (fig.2) is characterized by some properties such as, cross coupling of its inputs, external disturbances (gusts of wind, atmospheric pressure etc.), strong non-linearities, and structured and unstructured uncertainties (neglected dynamics, variations of aerodynamic and inertial parameters, etc.). In this regard, there exist lot of non-linearities and uncertainities associated with a quadrotor dynamics. The modelling of a quadrotor is derived considering the following assumptions [7]: (1) the structure is assumed to be rigid and strictly symmetrical (2) the torque is proportional to the DC motor voltage and the quadrotor reference is supposed to be confined within its gravity center. Figure 2 shows the coordinate system, with is composed of a fixed frame O_e and a body frame O_b. Using Newton-Euler formalism, the dynamic equations of the Quadrotor are given in (1) [4]:

$$\begin{cases} \ddot{\phi} = \dfrac{(I_y - I_z)}{I_x}\dot{\theta}\dot{\psi} - \dfrac{J_r}{I_x}\overline{\Omega}_r\dot{\theta} - \dfrac{K_{fax}}{I_x}\dot{\phi}^2 + \dfrac{l}{I_x}u_2 \\ \ddot{\theta} = \dfrac{(I_z - I_x)}{I_y}\dot{\phi}\dot{\psi} + \dfrac{J_r}{I_y}\overline{\Omega}_r\dot{\phi} - \dfrac{K_{fay}}{I_y}\dot{\theta}^2 + \dfrac{l}{I_y}u_3 \\ \ddot{\psi} = \dfrac{(I_x - I_y)}{I_z}\dot{\theta}\dot{\phi} - \dfrac{K_{faz}}{I_z}\dot{\psi}^2 + \dfrac{l}{I_z}u_4 \\ \ddot{x} = -\dfrac{K_{ftx}}{m}\dot{x} + \dfrac{1}{m}u_x u_1 \\ \ddot{y} = -\dfrac{K_{fty}}{m}\dot{y} + \dfrac{1}{m}u_y u_1 \\ \ddot{z} = -\dfrac{K_{ftz}}{m}\dot{z} - g + \dfrac{C\phi C\theta}{m}u_1 \end{cases} \tag{1}$$

Where, m is the quadrotor mass, J_r is rotor inertia I_x, I_y and I_y are inertia moments, K_{ftx}, K_{fty} and K_{ftz} are the coefficients of aerodynamic friction, K_{fax}, K_{fay} and K_{faz} are the drag coefficients, $\overline{\Omega}_r$ is the angular velocity expressed in the fixed frame, $\overline{\Omega}_r = \omega_1 - \omega_2 + \omega_3 - \omega_4$ and the control inputs are defined as,

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} b & b & b & b \\ 0 & -lb & 0 & lb \\ -lb & 0 & lb & 0 \\ d & -d & d & -d \end{bmatrix} \times \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix}$$

With: b, d and l are thrust factor, drag factor and lever respectively.

If we chose the following state space variables as $[x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}]^T = [x, \dot{x}, y, \dot{y}, z, \dot{z}, \phi, \dot{\phi}, \theta, \dot{\theta}, \psi, \dot{\psi}]^T$:

System (3) can be rewritten as follow:

$$\begin{cases} \dot{X}_1 = X_2 \\ \dot{X}_2 = f(X) + g(X)U(t) \end{cases} \tag{2}$$

Where

$$f(X) = \begin{bmatrix} a_1 x_4 x_6 + a_2 x_2^2 + a_3 \overline{\Omega} x_4 \\ a_4 x_2 x_6 + a_5 x_4^2 + a_6 \overline{\Omega} x_2 \\ a_7 x_2 x_4 + a_8 x_6^2 \\ a_9 x_8 \\ a_{10} x_{10} \\ a_{11} x_{12} - g \end{bmatrix} \text{ and } g(X) = \begin{bmatrix} 0 & b_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & b_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & b_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{u_1}{m} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{u_1}{m} \\ \frac{\cos x_1 \cos x_3}{m} & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

In order to design the controllers for the trajectory-tracking mode, the error model (2) can be written as six (6) sub-systems as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x) + g(x)u(t) \end{cases} \tag{3}$$

3. NTSMC for the quadrotor trajectory tracking

The design of NTSMC is based on the choice of a nonlinear typical sliding mode surface defined as the following:

$$S = \lambda sign(\dot{x})|\dot{x}|^{\gamma} + x \tag{4}$$

Where: $\lambda \succ 0$, $1 \prec \gamma = \frac{p}{q} \prec 2$ and p and q are positive odd integers that satisfy the condition $p \succ q$.

The control law u_{Total} is composed by two terms as

$$u_{Total} = u_{eq} + \Delta u \tag{5}$$

The first term (u_{eq}) is the equivalent control law, is obtained with respect to the condition $\dot{S} = 0$. The second term (Δu) roles is the discontinuous control law, it is used in order to force and maintain the system trajectories near to the sliding surface. In the case of quadrotor the sliding surface is given as

$$S_n = \lambda_i sign(\dot{e}_i)|\dot{e}_i|^{\gamma} + e_i \tag{6}$$

where: $e_i = x_i - x_{id}$, $i = 1,3,5,7,9,11$ and $n = x, y, z, \phi, \theta, \psi$ and $\lambda_i \in R$

Considering the surface $S_\phi = \lambda_7 sign(\dot{e}_7)|\dot{e}_7|^{\gamma} + e_7$ and showing the controldesign steps for the variable $x_7 = \phi$ with the choice of the following candidate Lyapunov function:

$$V_{\phi}=\frac{1}{2}S_{\phi}^{2} \tag{7}$$

To guarantee stability in the sense of Lyapunov, one must have $\dot{V}_{\phi}\prec 0$, which leads to $\dot{S}_{\phi}S_{\phi}\prec 0$; which is the necessary slip condition. The derivative of the slip surface NTSMCM $\dot{S}_{\phi}$ is given as follows:

$$\dot{S}_{\phi}=\lambda_{7}\gamma sign(\dot{e}_{7})\ddot{e}_{7}\left|\dot{e}_{7}\right|^{\gamma-1}+\dot{e}_{7}=0$$

$$\dot{S}_{\phi}=[h_{1}x_{10}x_{12}+h_{2}x_{10}+h_{6}u_{2}]-\ddot{x}_{7d}+\frac{1}{\lambda_{7}\gamma}\left|x_{8}-\dot{x}_{7d}\right|^{2-\gamma}=0$$

Tacking into account of the discontinuous control par $\Delta u=-k_{4}sign(S_{\phi})$, the control law is

$$u_{2}=\frac{1}{h_{6}}\left\{\ddot{x}_{7d}-h_{1}x_{10}x_{12}-h_{2}x_{10}-\frac{1}{\lambda_{7}\gamma}\left|x_{8}-\dot{x}_{7d}\right|^{2-\gamma}-k_{4}sign(S_{\phi})\right\} \tag{8}$$

Using the same procedure for the all outputs of the quadrotor, NTSMC the control law is given as

$$\left.\begin{aligned}
u_{1}&=\frac{m}{\cos(x_{7})\cos(x_{9})}\left\{\ddot{x}_{5d}+\frac{k_{z}}{m}x_{6}^{2}+g-\frac{1}{\lambda_{5}\gamma}\left|x_{6}-\dot{x}_{5d}\right|^{2-\gamma}-k_{3}sign(S_{z})\right\}\\
u_{x}&=\frac{m}{u_{1}}\left\{\ddot{x}_{1d}+\frac{k_{x}}{m}x_{2}^{2}-\frac{1}{\lambda_{1}\gamma}\left|x_{2}-\dot{x}_{1d}\right|^{2-\gamma}-k_{1}sign(S_{x})\right\}\\
u_{y}&=\frac{m}{u_{1}}\left\{\ddot{x}_{3d}+\frac{k_{y}}{m}x_{4}^{2}-\frac{1}{\lambda_{3}\gamma}\left|x_{4}-\dot{x}_{3d}\right|^{2-\gamma}-k_{2}sign(S_{y})\right\}\\
u_{2}&=\frac{1}{h_{6}}\left\{\ddot{x}_{7d}-h_{1}x_{10}x_{12}-h_{2}x_{10}-\frac{1}{\lambda_{7}\gamma}\left|x_{8}-\dot{x}_{7d}\right|^{2-\gamma}-k_{4}sign(S_{\phi})\right\}\\
u_{3}&=\frac{1}{h_{7}}\left\{\ddot{x}_{9d}-h_{3}x_{8}x_{12}-\frac{1}{\lambda_{9}\gamma}\left|x_{10}-\dot{x}_{9d}\right|^{2-\gamma}-k_{7}sign(S_{\theta})\right\}\\
u_{4}&=\frac{1}{h_{8}}\left\{\ddot{x}_{11d}-h_{5}x_{8}x_{10}-\frac{1}{\lambda_{11}\gamma}\left|x_{12}-\dot{x}_{11d}\right|^{2-\gamma}-k_{6}sign(S_{\psi})\right\}
\end{aligned}\right\} \tag{9}$$

with $h_{1}=\frac{I_{y}-I_{z}}{I_{x}}, h_{2}=\frac{aJ_{rz}}{I_{x}}, h_{3}=\frac{I_{z}-I_{x}}{I_{y}}, h_{4}=\frac{aJ_{rz}}{I_{y}}\ h_{5}=\frac{I_{x}-I_{y}}{I_{z}}, h_{6}=\frac{d}{I_{x}}, h_{7}=\frac{d}{I_{y}},\ h_{8}=\frac{1}{I_{z}}$

4. Particular swarm optimization

Particle Swarm Optimization (PSO) algorithm is a bio-inspired stochastic method, mimic the behaviours of bird flock and fish school proposed in 1995 [7]. In this algorithm, computational resources are allocated by a group of artificial particles. These particles exploit their individual and environmental information to find the target (the best solution). The performances are measured based on a quality of one or several objective fitness function. The concept of PSO consists of defining first the best local position of each particle and best global position $gbest$ of overall the set at each iteration. Each particle tries to change its current position and velocity depending on the distance between its current position and $pbest$, and the distance between its current position and $gbest$. At each iteration t, a new position and velocity is updated for the i^{th} particle as

$$v_{i,j}(t+1)=vw_{i,j}(t)+c_{1}r_{1}^{t}\left\{pbest_{i,j}-x_{i,j}(t)\right\}+c_{2}r_{2}^{t}\left\{gbest_{i,j}-x_{i,j}(t)\right\} \tag{10}$$

$$x_{i,j}(t+1) = x_{i,j}(t) + v_{i,j}(t+1) \tag{11}$$

where: $j = 1,2..D$, w, c_1 and c_2 are positive constants, called respectively, inertia coefficient; acceleration coefficients, r_1 and r_2 are both random numbers in [0;1]. *D* dimension of the search space. $vw_{i,j}(t)$ is term corresponds to the particle displacement inertia, which lets to parameter w controls the influence of the displacement direction. $c_1 r_1^t \{pbest_{i,j} - x_{i,j}(t)\}$ corresponds to the cognitive part, where c_1 controls the cognitive behavior of the particle. $c_2 r_2^t \{gbest_{i,j} - x_{i,j}(t)\}$ corresponds to the social part, c_2 controls the social ability of the particle. Once the displacement of the particles is down, the new positions are obtained, in this fact $pbest$ and $gbest$ are updated, at iteration $t+1$, according to 10 and 11.

Objective fitness function :

In order to find the optimal parameters of the NTSMC an objective fitness function J was proposed to be minimized (equation 12). This last is composed of two parts $J_1(e)$ and $J_2(u)$, the relevance of the controller in terms of tracking and consumption of the energy stored in the battery and the precision the speed depends on the rate α and $1-\alpha$ which are given respectively to the term J_1 and J_2. To allow the quadrotor to fulfill these missions in all efficiency, we chose the cost function $J(e,u)$ to gain speed and accuracy $J_1(e)$ in terms of tracking and also in terms of power consumption energy $J_2(u)$, the results obtained after optimization will show the effect of choice on the synthesis of the parameters and the cost function $J(e,u)$.

$$J(e,u) = \alpha J_1(e) + (1-\alpha) J_2(u) \tag{12}$$

With

$$J_1(e) = \frac{1}{K}\sum_{1}^{N}(te_1^2 + te_3^2 + te_5^2 + te_7^2 + te_9^2 + te_{11}^2) \text{ and } J_2(e) = \frac{1}{K}\sum_{1}^{N}(u_1^2 + u_2^2 + u_3^2 + u_4^2 + u_x^2 + u_y^2)$$

where *K* is the number of samples ***Stability analysis***

Considering the following Lyapunov candidate function $V = \frac{1}{2}S^2$, the sufficient condition of stability is $\dot{V} \le -\Psi(\dot{e})|S|$ with $\Psi(\dot{e}) = k\gamma / \lambda(\dot{e})^{\gamma-1}$

Moreover, it is very important to mention that the optimized parameters will not affected the stability of the system in a closed loop.

5. Simulation and discussions

In order to show the effectiveness of the proposed approach to control the quadrotor system, the first step consists of the optimization of the NTSM controller using PSO, where 12 parameters are optimized and PSO parameters is defined arbitrarily. The swarm size is 20 particles and number of iterations is 100. The acceleration coefficients c_1 and c_2 are 1.8 and 1.5 respectively. r_1 and r_2 are random values in]0,1], generated at each iteration, they represent a uniform distribution. Six tests were conducted the best-optimized solution was selected. The corresponding parameters to the best solution are listed in Table 1. Optimized fitness function is shown in Fig. 3. The Second step, is the application of the optimized controller in trajectory tracking mode Fig. 4 and Fig. 5 present the obtained results. These results present the comparison of NTSMC and classical Sliding Mode Controller (SMC). Table. 2 gives the obtained performances for each controller.

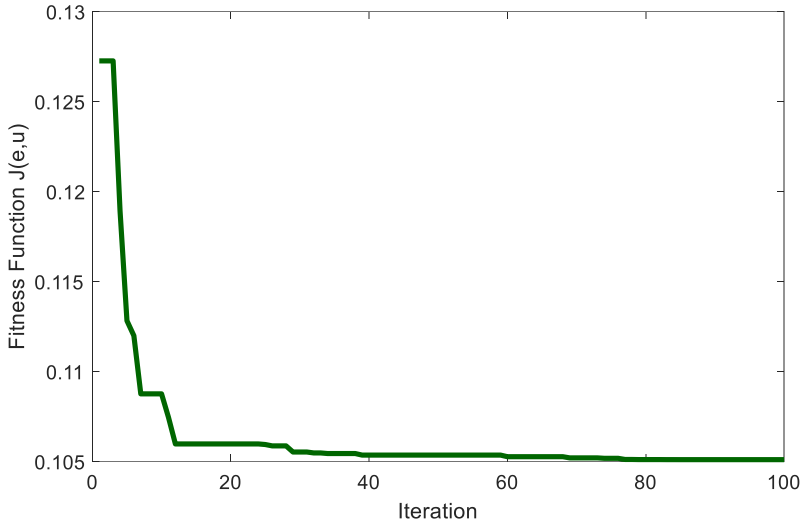

Figure. 3. Fitness function J(e,u)

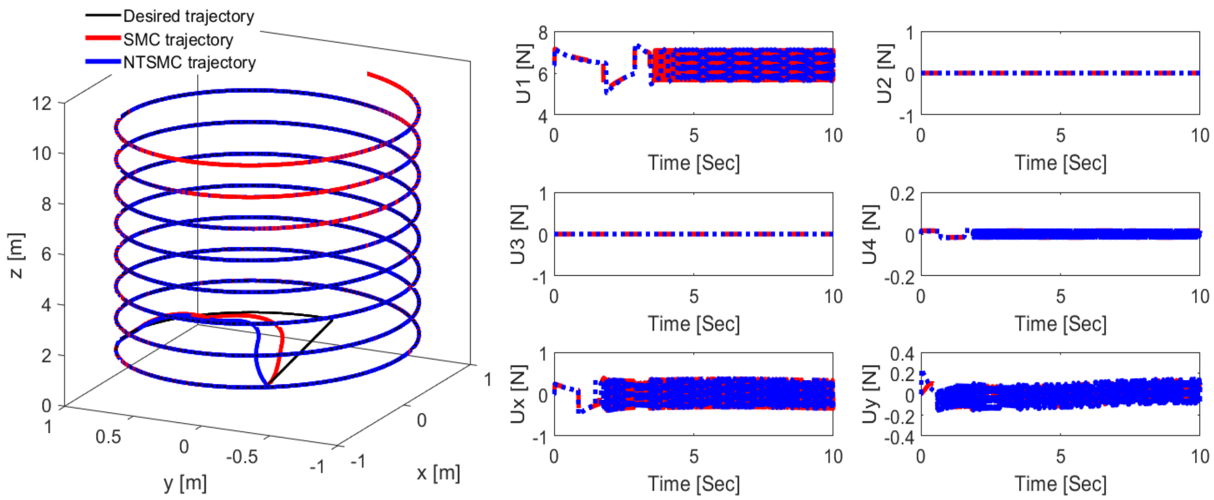

Figure.4. Trajectory tracking and control signals

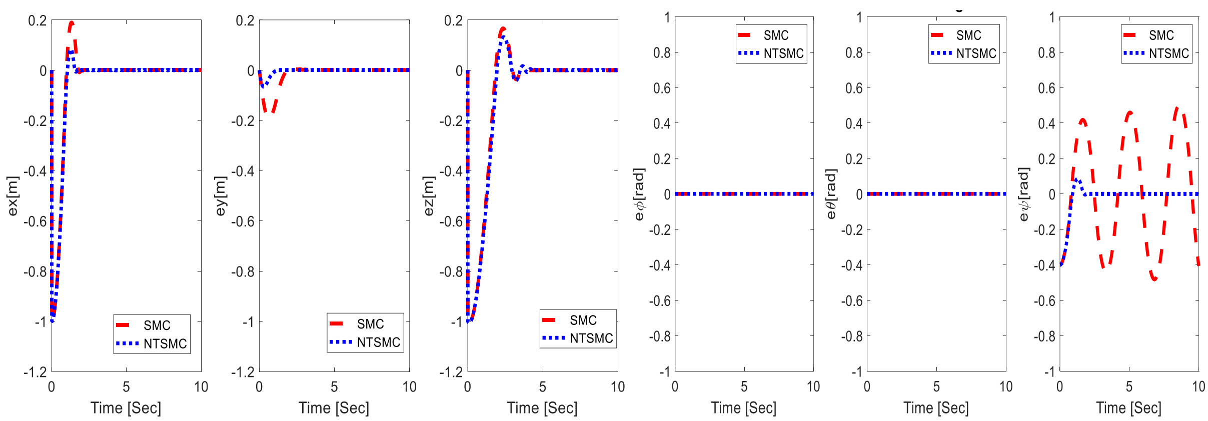

Figure.5. Trajectory tracking errors

Table 1. SMC & NTSMC optimized parameters

Parameter	k_1	k_2	k_3	k_4	k_5	k_6
value	2.9255	0.9130	1.0944	47.4752	1.2632	1.2158
Parameter	λ_1	λ_3	λ_5	λ_7	λ_9	λ_{11}
value	0.1061	1.1725	0.0938	10.1978	2.7721	0.1973

The obtained results confirmed the quality of the proposed controller, as we can see in Fig.5 all errors are converged to zero rapidly, control signals presents some chattering (Fig. 4) that can be treated by saturation function.

Table 2. SMC & NTSMC performances

Performances	$J(e)=\sum_{i=1}^{6}\int_{0}^{t_f} e^2 dt$	$J(u)=\sum_{i=1}^{6}\int_{0}^{t_f} u^2 dt$	$J_{\sum} = J(e)+J(u)$
SMC	6.2104e+03	1.6966e+11	1.6966e+11
NTSMC	**156.9302**	**4.1289e+05**	**4.1305e+05**

Table. 2 shows that NTSMC is better than SMC performances from precision and energy consumption point of view.

6. Conclusion

In this work, we proposed a nonlinear optimized controller called ONTSMC for trajectory tracking of quadrotor system. This system is used in order to inspect of solar panels field. The objective is to have an accurate controller to focus on any anomaly in the panels such as presence of sand, defaults in the panels, etc. and the obtained results shows the effectiveness of the proposed controller. In perspective, it is planed to test this controller in the presence of unfavorable atmospheric conditions.

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