On High-Precision Three-Axis Attitude Control Scheme through Hybrid Finite-Time Sliding Mode Approach

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Abstract— **High-precision three-axis attitude control scheme is vitally important to deal with the overactuated spacecraft, as long as the overall performance through rapid response can be in general acquired. Due to the fact that the rigid-flexible spacecraft is somehow applicable, in so many academic and real environments, there is a consensus among experts of this field that the new insights in developing the present complicated systems modeling and control are highly recommended with respect to state-of-the-art. The new hybrid control scheme presented here is organized in line with the linear approach, which includes the proportional derivative based quadratic regulator and the nonlinear approach, which includes finite-time sliding mode control, as well. It should be noted that the three-axis angular rates of spacecraft under control are all dealt with in inner closed loop control and the corresponding rotation angles are also dealt with in outer closed loop control, synchronously.**

Index Terms— **hybrid three-axis attitude control scheme, proportional derivative based linear quadratic regulator, finite-time sliding mode control, overactuated spacecraft.**

I. INTRODUCTION

The attitude finite-time control scheme plays a significant role in the overall performance of the spacecraft. Up to now, the known control approach in this area may generally be improved, while a number of modifications are made with respect to state-of-the-art. In the same way, the new control scheme proposed here is realized based on the hybrid control approach, which is now working in association with linear and nonlinear approaches, synchronously, in the presence of uncertainties and disturbances. Based on the matter presented here, a linear part of control approach under optimum coefficients is employed to deal with the whole of rotation angles of the spacecraft, since a nonlinear part of control is also employed to cope with the whole of angular rates of the spacecraft.

Concerning the recent potential research in this area, Shahmohamadi et al. present active nutation control through an axial reaction wheel, whilst Xu et al. consider Takagi–Sugeno fuzzy model based robust dissipative control in flexible spacecraft under saturated time-delay input [1]-[2]. Zhang et al. propose attitude control and sloshing suppression in liquid-filled spacecraft in the presence of sinusoidal disturbance and Chen et al. is to control formation through a virtual spring-damper mesh [3]-[4]. Huang et al. research is to deal with a neural network-based adaptive second order sliding mode control in case of Lorentz-augmented formation, while Warier et al. research is to cope with line-of-sight based formation keeping with attitude control of a number of spacecrafts [5]-[6]. Afterwards, Jikuya et al. focus on attitude maneuver with a variable-speed double gimbal control moment gyro and Zou et al. work is also focus on the attitude tracking control through robust adaptive neural network augmenting sliding mode control [7]-[8]. There are Hu et al. work to support an idea of smooth finite-time attitude tracking control, as long as Park et al. idea is to handle attitude control under inertia uncertainties through minimal kinematic parameters [9]-[10]. Yang et al. work is to deal with attitude formation control with time-varying delays and switching topology and Sun et al. work is to handle robust attitude control for autonomous proximity [11]-[12]. Felicetti et al. explore analytical and numerical investigations in the area of formation control through electrostatic forces and Guglielmo et al. dedicate spacecraft relative guidance through spatio-temporal resolution in atmospheric density forecasting [13]-[14]. Meng et al. consider a new geometric guidance approach in the field of near-distance rendezvous problem and Warier et al. survey line-of-sight based spacecraft attitude and position tracking control [15]-[16]. Guarnaccia et al. research is to present suboptimal full motion control by theory and experimentation, while Zou et al. research is to consider the application of distributed finite-time velocity-free attitude coordination control to formations [17]-[18]. Zavoli et al. propose spacecraft dynamics with the action of Y-dot magnetic control law and Xia et al. present robust neural control in rendezvous and docking under input saturation as well as Huang wt al. consider attitude takeover control for post-capture through space robot [19]-[21]. Sabatini et al. in 2014 propose a method for delay compensation in the area of attitude control of flexible spacecraft [22]. In this research, the strategy to compensate for delays is elaborated by means of a free floating platform, replicating the spacecraft attitude dynamics. The platform is equipped with thrusters through the on–off modulation of the linear quadratic regulator control law. A prediction of the state can be made through the mathematical model of the system in line with the rigid and elastic

Manuscript received August 31, 2015; accepted September18, 2016
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measurements enable, since the control is evaluated to make the predicted state relevant to a delayed time. Zheng et al. in 2014 suggest an autonomous attitude coordinated control for a spacecraft [23]. Three controllers including autonomous attitude coordinated control approach, a robust adaptive attitude coordinated control approach and finally a filtered robust adaptive attitude coordinated control approach are all realized to overcome the case in different situations of input constraints, model uncertainties, and external disturbances.

Yang et al. in 2014 propose nonlinear attitude tracking control for spacecraft [24]. They have tried to deal with the attitude tracking control for spacecraft formation with communication delays. In this way, the sliding mode control in line with adaptive attitude synchronization control is realized. Afterwards, a non-smooth feedback function is used, since a class of nonlinear control approaches are designed for the attitude tracking of spacecraft. Huo et al. in 2014 suggest finite-time fault tolerant attitude stabilization control for rigid spacecraft [25]. In this work, a sliding mode control scheme is proposed to solve the problem of attitude stabilization for a rigid spacecraft.

There is a precise reconstruction with zero observer error in finite time, since the reconstructed information is acquired to synthesize a nonsingular terminal sliding mode attitude control approach together with the system states. In the Du et al. in 2014 research, an attitude synchronization control for a class of flexible spacecraft is proposed to deal with the problem of attitude synchronization for a class of flexible spacecraft [26]. Using the backstepping realization in association with the neighbor-based design rule, a distributed attitude control law is suggested. It is there shown that the attitude synchronization could asymptotically be achieved, while the induced vibrations are suppressed under the proposed control law, simultaneously.

Song et al in 2014 work is to realize finite-time control for nonlinear spacecraft attitude via terminal sliding mode approach [27]. In their research, a terminal sliding mode control approach with double closed loops is suggested to deal with spacecraft attitude control problem. These laws are included in an inner and outer control loops. The strategy is proposed by using Lyaponov's concept to ensure the occurrence of the finite-time sliding motion. Lu et al. in 2013 research is to deal with an adaptive attitude tracking control for rigid spacecraft with finite-time convergence [28]. In this research work, the attitude tracking control problem with finite-time is addressed for rigid spacecraft with external disturbances and inertia uncertainties. As reported, a fast nonsingular terminal sliding mode surface is designed without any constraint. The proposed control laws are organized in line with adaptive control architecture, as chattering-free. Yang et al. in 2012 review spacecraft attitude determination and control using Quaternion based method [29]. In this review, the quaternion based methods are first discussed for spacecraft attitude determination and control. In the mentioned quaternion based control system, some reduced quaternion models using vector component of the quaternion in the state space models are considered. Afterwards, some methods with the following features, i.e. analytic solution of regulator and also the reduced disturbance effect with stable nonlinear spacecraft system are presented.

Zou et al. in 2011 work is presented an adaptive fuzzy fault-tolerant attitude control of spacecraft [30]. They investigate the attitude control of spacecraft, since unknown mass moment of inertia matrix, external disturbances, actuator failures, and input constraints are all existed. In this presentation, a robust adaptive control approach is proposed via fuzzy logic in association with backstepping approach. There is a unit quaternion to describe the attitude of spacecraft for global representation. It should be noted that the uncertainty can be estimated through a fuzzy logic system, while an adaptive mechanism is derived. In order to present this literature's survey in the concise form, the proceeding investigated results are all given briefly. Hu et al. work in 2013 is to realize robust attitude control for spacecraft under assigned velocity and control constraints [31], while Cai et al. in 2014 work is to deal with the leader-following attitude control of multiple rigid spacecraft systems. Hereinafter [32], Kuo et al. in 2012 work is presented in the area of attitude dynamics and control of miniature spacecraft via pseudo-wheels [33], once Zhang et al. in 2014 research is given in attitude control of rigid spacecraft with disturbance generated by time varying exo-systems [34]. Erdong et al. in 2008 propose robust decentralized attitude coordination control of spacecraft formation [35].

As are obvious, the whole of above-referenced research in association other related ones are all tried to address some efficient methods to deal with this complicated system. In the same way, the proposed hybrid control approach has now made another new effort, while its main differences w. r. t. these methods are given in the approach's structure and the corresponding results.

The remainder of the manuscript is organized as follows: The proposed hybrid control approach is first given in Section 2. The simulation results are then given in Section 3. Finally, the research concludes in Section 4.

I. THE PROPOSED HYBRID CONTROL APPROACH

The proposed hybrid control approach is here designed in line with the nonlinear and also the linear approaches, correspondingly. Regarding those obtained from nonlinear one, the sliding mode control approach is realized based upon the following n-order nonlinear system

$$x^{(n)} = f(x) + b(x)u \tag{1}$$

where the state vector of the system under control is taken as $X = [x \quad \dot{x} \quad \dots \quad x^{(n-1)}]$ and the input of the system is also taken as u. Here $f(x)$ is given as an unknown function with bounded uncertainties, i.e. $\left|f(X) - \hat{f}(X)\right| \leq F(X)$. By assuming $\tilde{X} = X - X_d = \left[\tilde{x}_d \quad \tilde{x}_d \quad \dots \quad \tilde{x}_d{}^{(n-1)}\right]$ as the state tracking error and also $s(X;t) = \left(\frac{d}{dt} + \lambda\right)^{n-1}$ as the sliding surface with the siding condition, i.e. $\dot{s}s \leq -\eta.sgn(s)s = -\eta|s|$, it is easily possible to realize the control approach, in the following form

$$\begin{aligned} u = u_0 - \hat{b}^{-1}k.sgn(s) & \\ = -\hat{b}^{-1}\Big[-f + \ddot{X}_d - \lambda\dot{\tilde{X}} & \\ - k.sgn(s)\Big] & \end{aligned} \tag{2}$$

Here, $u_0 = \hat{b}^{-1}\underbrace{\left[-\hat{f} + \ddot{X}_d - \lambda\dot{\tilde{X}}\right]}_{u'}$ is realized, since the parameters including $\beta^{-1} \le \frac{\hat{b}}{b} \le \beta,\ \beta = (b_{max}/b_{min})^{1/2}$, $\hat{b} = \sqrt{b_{min}b_{max}}$ and $k \ge \beta(F+\eta) + (\beta-1)|u'|$ are all addressed. Now, the present sliding mode control approach should be realized in the present spacecraft under control for the purpose of coping with the three axes angular rates, i.e. $p = \omega_x, q = \omega_y$ and $r = \omega_z$. In this regard, by addressing ω_{xd}, ω_{yd} and ω_{zd}, as the desired angular rates, the angular rates errors are taken as $\begin{pmatrix}\tilde{\omega}_x\\ \tilde{\omega}_y\\ \tilde{\omega}_z\end{pmatrix} = \begin{pmatrix}\omega_x - \omega_{xd}\\ \omega_y - \omega_{yd}\\ \omega_z - \omega_{zd}\end{pmatrix}$. The outcomes in realizing the control effort have to satisfy the following

$$\begin{pmatrix}\tilde{\omega}_x(\dot{\omega}_x - \dot{\omega}_{xd})\\ \tilde{\omega}_y(\dot{\omega}_y - \dot{\omega}_{yd})\\ \tilde{\omega}_z(\dot{\omega}_z - \dot{\omega}_{zd})\end{pmatrix} \le \eta \begin{pmatrix}|\omega_x - \omega_{xd}|\\ |\omega_y - \omega_{yd}|\\ |\omega_z - \omega_{zd}|\end{pmatrix} \tag{3}$$

The control effort with $\eta = cte$ in association with other related terms could be rewritten as

$$\begin{pmatrix}\tilde{\omega}_x(f(\omega_x) + u_x - \dot{\omega}_{xd})\\ \tilde{\omega}_y(f(\omega_y) + u_y - \dot{\omega}_{yd})\\ \tilde{\omega}_z(f(\omega_z) + u_z - \dot{\omega}_{zd})\end{pmatrix} \le \eta \begin{pmatrix}|\omega_x - \omega_{xd}|\\ |\omega_y - \omega_{yd}|\\ |\omega_z - \omega_{zd}|\end{pmatrix} \tag{4}$$

The investigated nonlinear control effort could be realized via

$$\begin{pmatrix}u_x\\ u_y\\ u_z\end{pmatrix} = \begin{pmatrix}-\hat{f}(\omega_x) + \dot{\omega}_{xd} - K_x\, sgn(\omega_x - \omega_{xd})\\ -\hat{f}(\omega_y) + \dot{\omega}_{yd} - K_y\, sgn(\omega_y - \omega_{yd})\\ -\hat{f}(\omega_z) + \dot{\omega}_{zd} - K_z\, sgn(\omega_z - \omega_{zd})\end{pmatrix} \tag{5}$$

where $K_i = F(\omega_i) + \eta_i$; $F(\omega_i) = -\alpha_1\hat{f}(\omega_i)$; $i = x, y, z$ and there is

$$\begin{pmatrix}\hat{f}(\omega_x)\\ \hat{f}(\omega_y)\\ \hat{f}(\omega_z)\end{pmatrix} = -\alpha_2 \begin{pmatrix}\frac{I_{zz} - I_{yy}}{I_{xx}}.\omega_y.\omega_z\\ \frac{I_{xx} - I_{zz}}{I_{yy}}.\omega_x.\omega_z\\ \frac{I_{yy} - I_{xx}}{I_{zz}}.\omega_y.\omega_x\end{pmatrix} \tag{6}$$

where I_{xx}, I_{yy} and I_{zz} denote the three-axis spacecraft moment of inertia. And $\alpha_1 = \frac{1}{3}$ and $\alpha_2 = \frac{3}{2}$ are respectively taken. Now, regarding the linear one, the present spacecraft can be dealt with through the proportional derivative (PD) based linear quadratic regulator (LQR) approach, which is realized in the outer loop to track the angular rotations, i.e. φ, θ and ψ entitled *TPhi*, *TTeta* and *TPsi*, respectively, based upon its referenced angular rotations, i.e. φ_d, θ_d and ψ_d, entitled *RPhi*, *RTeta* and *RPsi*, respectively. The whole of control coefficients are acquired via the LQR to optimize its performance index. Here, the PD based LQR approach is realized in line with the linear state space system, given by the following

$$\begin{cases}\dot{X} = \begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}X + \begin{bmatrix}0\\ 1\end{bmatrix}u\\ u = \frac{\tau_i}{I_i}\end{cases} \tag{7}$$

where X is taken as the state vector and u, which is organized based upon τ_i, I_i, i.e. the torque and the moment of inertia in ith axis as the system inputs. In the same way, the performance index is realized as

$$\begin{cases}V = \int_0^\infty (x_1^2 + x_2^2 + R\,u^2)dt\\ R = \frac{1}{c^2}\end{cases} \tag{8}$$

The PD based LQR control effort; $u = -KX = -k_{p_p}(x_1 - x_0) - k_{d_i}x_2$, are designed to optimize the present performance index. In one such case, by supposing $P = \begin{bmatrix}p_{11} & p_{12}\\ p_{21} & p_{22}\end{bmatrix}$ as positive definite matrix, the Riccati equation, i.e. $A^*P + PA - PBR^{-1}B^*P + Q = 0$ can easily be dealt with to calculate P. Now, the PD based LQR coefficients could be resulted through $K = R^{-1}B^*P$ by

$$k_{p_i} = c\frac{I_i}{\tau_i}\ , k_{d_i} = \frac{I_i}{\tau_i}\sqrt{c^2 + 2c} \tag{9}$$

Finally, by addressing $\begin{pmatrix}e_x\\ e_y\\ e_z\end{pmatrix} = \begin{pmatrix}\varphi - \varphi_d\\ \theta - \theta_d\\ \psi - \psi_d\end{pmatrix}$ entitled errors of *PDx*, *PDy* and *PDz*, respectively, and $i = x, y$ and z, as the three axes, the linear control effort results by the following

$$\begin{pmatrix}u_x\\ u_y\\ u_z\end{pmatrix} = \begin{pmatrix}k_{px}e_x + k_{dx}\dot{e}_x\\ k_{py}e_y + k_{dy}\dot{e}_y\\ k_{pz}e_z + k_{dz}\dot{e}_z\end{pmatrix} \tag{10}$$

II. THE SIMULATION RESULTS

To consider the approach proposed here, at first, the outcomes are simulated, as long as the whole of parameters are calculated or initiated. Regarding the spacecraft moment of inertia, these ones as well as the pulse-width pulse-frequency (PWPF) parameters are traditionally tabulated based upon the related standard information that is easily available in this area via Table 1. By choosing $c = 5.0$, the coefficients of the linear term of control approach are calculated via Eq. (9), as tabulated in Table 2. Now, in order to consider the applicability and its efficiency of the proposed hybrid control approach, the investigated outcomes are now illustrated.

TABLE I
THE PARAMETRES USED IN THE PROPOSED APPROACH

	The spacecraft dynamics	The PWPF
1	$I_{xx} = 16$	$K_m = 5.0; T_m = 0.50$
2	$I_{yy} = 75$	$U_{on} = 0.8$
3	$I_{zz} = 75$	$U_{off} = 0.1$

TABLE II
THE COEFFICIENTS OF THE LINEAR TERMS OF CONTROL APPROACH

	The coefficients	
1	$K_{px} = 4.43$	$K_{dx} = 26.21$
2	$K_{py} = 12.44$	$K_{dy} = 73.63$
3	$K_{pz} = 12.55$	$K_{dz} = 74.24$

In one such case, the desired signals in there axes including referenced Phi; *RPhi*, referenced Teta; *RTeta*, and referenced Psi; *RPsi* are chosen as all shown in Fig. 1. As mentioned before, there are two closed loop control approaches, since the outer loop is realized in line with the above-referenced linear control approach and the inner loop is also realized in line with the above-referenced nonlinear control approach. Regarding the outer loop, Fig. 2 illustates the errors of the present linear control approach, synchronously, in there axes. As are obvious, they are to be about zero, in a finite time, accurately.

Subsequently, the tracked rotation angles in the three axes with respect to the referenced ones are all shown in Fig. 3. They indicate the appropriate outcomes by varying the referenced inputs in separated variations in the three axes with respect to time. To consider the results investigated in the proposed approach, the same spacecraft has been dealt with through a standard optimum PD, as benchmark approach. It is apparent that the realized PD parameters are the same as the PD organized in the outer loop of the proposed approach. By considering the outcomes, investigated here, in a careful manner, it comes to our attention that the proposed hybrid control approach is well behaved with respect to those obtained from the above-referenced benchmark, at each instant of time.

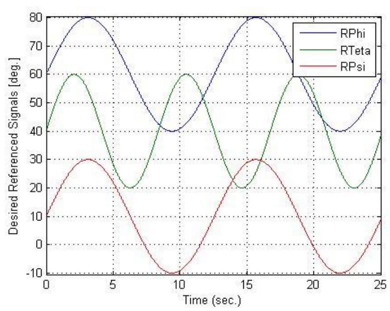

Fig 1. The referenced *RPhi, RTeta* and *Rpsi.*

III. CONCLUSION

A hybrid robust three-axis attitude finite-time control approach is proposed in this research. The control idea investigated here is in fact realized in line with a combination of linear and nonlinear control techniques in the both inner and the outer closed loops. In this case, an optimum linear approach is designed in the outer loop to cope with the rotation angles of the spacecraft under control, as long as the nonlinear control approach is also designed in the inner loop to cope with the

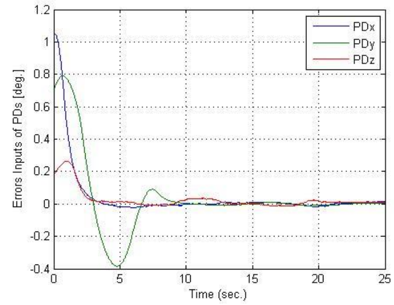

Fig 2. The *PDx*, *PDy* and *PDz* errors.

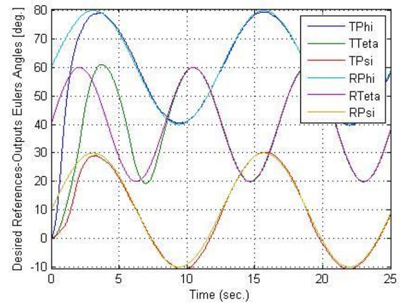

Fig. 3. The tracked rotation angles of the proposed approach in the three axes with respected to the referenced ones.

angular rates of the same spacecraft. At the end, the investigated outcomes are considered through a number of simulation programs that verify the approach performance and its efficiency, clearly.

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