State-of-the-art in Comprehensive Cascade Control Approach through Monte-Carlo Based Representation

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Abstract: The research relies on the comprehensive cascade control approach to be developed in the area of spacecraft, as long as Monte-Carlo based representation is taken into real consideration with respect to state-of-the-art. It is obvious that the conventional methods do not have sufficient merit to be able to deal with such a process under control, constantly, provided that a number of system parameters variations are to be used in providing real situations. It is to note that the new insights in the area of the research's topic are valuable to outperform a class of spacecrafts performance as the realizations of the acquired results are to be addressed in both real and academic environments. In a word, there are a combination of double closed loop based upon quaternion based control approach in connection with Euler based control approach to handle the three-axis rotational angles and its rates, synchronously, in association with pulse modulation analysis and control allocation, where the dynamics and kinematics of the present system under control are analyzed. A series of experiments are carried out to consider the approach performance in which the aforementioned Monte-Carlo based representation is to be realized in verifying the investigated outcomes.

1. Introduction

The new insight in the area of spacecraft control has become much more attractive during the last decade. In making an efficient effort, the present research attempts to address a potential comprehensive cascade control approach through Monte-Carlo based representation with respect to state-of-the-art. In a word, the traditional techniques may not deal with such a system under control in real situations. The core of finding in the proposed research is to handle the spacecraft, uniquely, as long as the investigated outcomes are efficient in a series of experiments. In order to consider the contribution of the topic, the background of potential control technique in the area of spacecraft is briefly focused. At first, Du et al. research is to deal with the attitude synchronization control to deal with the problem of synchronization [1]. Lu et al. research is to deal with an adaptive attitude tracking control with finite-time convergence [2]. Yang et al. review is to design the attitude determination and control through quaternion based classical method [3]. Zou et al. work is to explore adaptive fuzzy fault-tolerant attitude control and Cai et al. work is to deal with the leader-following attitude control [4]-[5]. Hereinafter, Zhang et al. research is to cope with the attitude of rigid system under control with disturbance that is provided by time varying exo-systems [6]. Erdong et al. propose robust decentralized attitude coordination control, while Lu et al. suggest a design of control strategy for attitude tracking with actuator saturation [7]-[8]. Moreover, Pukdeboon et al. consider the optimal sliding mode

control approach for attitude tracking via Lyapunov function [9].

Adaptive sliding mode control with its application to relative motion under input constraint is given by Wu et al. [10]. Zhang et al. focus on the attitude stabilization with disturbance generated by time varying uncertain exosystems, whilst Sun et al. suggest robust adaptive relative position tracking and attitude synchronization for rendezvous [11]-[12]. There are Park work that considers inverse optimal and robust nonlinear attitude control [13]. Hu et al. analyze attitude tracking control under actuator magnitude deviation and misalignment, where Shahi et al. explore Monte-Carlo based cascade control approach for real overactuated space systems [14]-[15].

Mazinan et al. investigate full quaternion based finite-time cascade attitude control approach via pulse modulation synthesis, autonomous space systems control incorporating automated maneuvers strategies in the presence of parameters uncertainties and finally three-axis detumbling mode control approach [16]-[18]. In making other efforts, Mazinan proposes maneuvers control subject to propellant engine modes, high-performance robust three-axis finite-time attitude control approach incorporating quaternion based estimation scheme, stability analysis of autonomous space systems in the presence of large disturbances based upon a Lyapunov-based constrained control strategy, high-precision full quaternion based finite-time cascade attitude control strategy, high-precision three-axis detumbling and pointing attitude control strategy, Lyapunov-based three-axis attitude intelligent control approach and finally hybrid robust three-axis attitude

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control approach in connection with a quaternion based model [19]-[25]. Hereinafter, Sun et al. look at composite control method to stabilize attitude in terms of Rodrigues parameters [26], Abdelrahman et al. consider attitude control via a combined state-dependent Riccati equation and adaptive neuro-fuzzy approach [27], Su et al. investigate velocity-free saturated proportional derivative control approach for asymptotic stabilization [28], Canuto et al. indicate satellite-to-satellite attitude control of a long-distance formation for the next generation gravity mission [29] and finally Liang et al. investigate robust decentralized attitude control of formations under time-varying topologies [30].

The rest of the manuscript is organized as follows: The comprehensive cascade control is first presented in Section 2. And then the results and discussion as well as the research' summery are given in Sections 3 and 4, respectively.

2. The Comprehensive Cascade Control
2.1 The Preliminary materials

The space model can be represented through the attitude dynamics and kinematics equations, where the first one is organized based on the following formula

$$\boldsymbol{\tau} = \frac{d\boldsymbol{H}_c}{dt} + \boldsymbol{\omega} \times \boldsymbol{H}_c \tag{1}$$

Here, $\boldsymbol{\tau}$ denotes three-axis control torques, $\boldsymbol{H}_c$ denotes three-axis angular momentum vector in the body coordinate that contains H_μ and finally $\boldsymbol{\omega}$ denotes three-axis angular velocity vector in the body coordinate that contains $\omega_\mu, \mu = x, y, z$. Now, by addressing the three-axis angular velocities, the three-axis control torques of the spacecraft are realized as

$$\begin{cases} \tau_x = \dot{H}_x + \omega_y H_z - \omega_z H_y \\ \tau_y = \dot{H}_y + \omega_z H_x - \omega_x H_z \\ \tau_z = \dot{H}_z + \omega_x H_y - \omega_y H_x \end{cases} \tag{2}$$

The attitude dynamics equation can easily be presented in Eq. (3)

$$\begin{cases} \dot{\omega}_x = \frac{\tau_x}{I_x} - \frac{(I_z - I_y)}{I_x} \omega_y \omega_z \\ \dot{\omega}_y = \frac{\tau_y}{I_y} - \frac{(I_x - I_z)}{I_y} \omega_x \omega_z \\ \dot{\omega}_z = \frac{\tau_z}{I_z} - \frac{(I_y - I_x)}{I_z} \omega_x \omega_y \end{cases} \tag{3}$$

Now, $\boldsymbol{q}_s$ can be presented in four dimensional space as follows

$$\boldsymbol{q}_s = q_{s0} + iq_{s1} + jq_{s2} + kq_{s3} \tag{4}$$

It is to note that $q_{si}; i = 0, 1, 2, 3$ has one real and three imaginary elements and also the conditions $\|\boldsymbol{q}_s\| = 1$ should be satisfied. The relations between $\omega_x, \omega_y, \omega_z$ and the q_{si} can be presented by

$$\begin{bmatrix} \dot{q}_{s1} \\ \dot{q}_{s2} \\ \dot{q}_{s3} \\ \dot{q}_{s4} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & -\omega_x & -\omega_y & -\omega_z \\ \omega_x & 0 & \omega_z & -\omega_y \\ \omega_y & -\omega_z & 0 & \omega_x \\ \omega_z & \omega_y & -\omega_x & 0 \end{bmatrix} \begin{bmatrix} q_{s1} \\ q_{s2} \\ q_{s3} \\ q_{s4} \end{bmatrix} \tag{5}$$

And the relations between ϕ, θ, ψ and q_{si} are now also given by

$$\begin{cases} q_{s0} = \cos\left(\frac{\psi}{2}\right)\cos\left(\frac{\theta}{2}\right)\cos\left(\frac{\varphi}{2}\right) + \sin\left(\frac{\psi}{2}\right)\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{\varphi}{2}\right) \\ q_{s1} = \cos\left(\frac{\psi}{2}\right)\cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\varphi}{2}\right) - \sin\left(\frac{\psi}{2}\right)\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{\varphi}{2}\right) \\ q_{s2} = \cos\left(\frac{\psi}{2}\right)\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{\varphi}{2}\right) + \sin\left(\frac{\psi}{2}\right)\cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\varphi}{2}\right) \\ q_{s3} = \sin\left(\frac{\psi}{2}\right)\cos\left(\frac{\theta}{2}\right)\cos\left(\frac{\varphi}{2}\right) - \cos\left(\frac{\psi}{2}\right)\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{\varphi}{2}\right) \end{cases} \tag{6}$$

Finally, the Euler angles can easily be calculated as

$$\begin{cases} \tan(\varphi) = \frac{2(q_{s1}q_{s2} + q_{s0}q_{s3})}{q_{s0}^2 + q_{s1}^2 - q_{s2}^2 - q_{s3}^2} \\ \sin(\theta) = -2(q_{s1}q_{s3} - q_{s0}q_{s2}) \\ \tan(\psi) = \frac{2(q_{s2}q_{s3} + q_{s0}q_{s1})}{q_{s0}^2 - q_{s1}^2 - q_{s2}^2 + q_{s3}^2} \end{cases} \tag{7}$$

2.2 The Approach Realization

The approach realization is based upon double closed loop to deal with the rotational angles and its rates in a number of propellant engine modes including on and off, respectively, as illustrated in Fig. 1. The results, acquired to handle engine on mode, is related to the Euler angles, where the same ones to handle engine off mode is related to quaternion, as well.
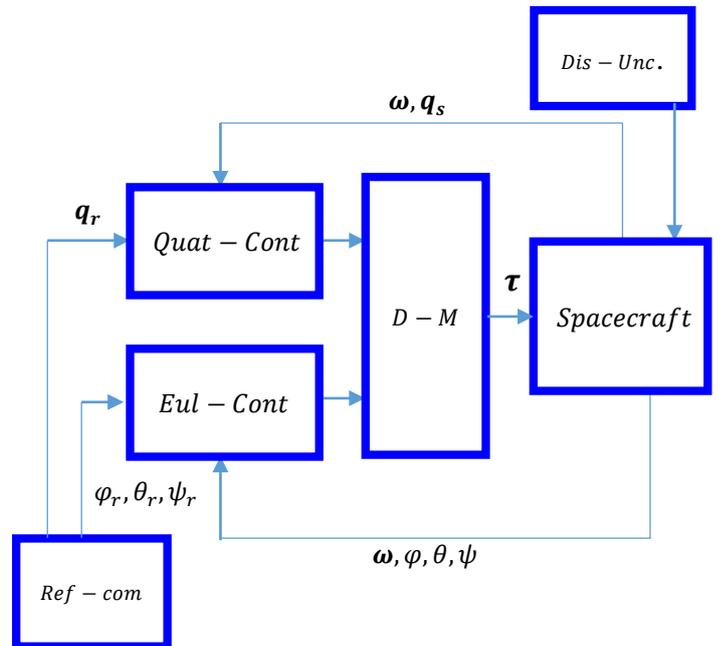
Fig. 1. The proposed comprehensive cascade control approach.

In fact, it is to note that the off mode is handled through quaternion based control approach; $Quat - Cont$, whilst the on mode is handled through Euler based control approach; $Eul - Cont$, where the decision making system; $D - M$, is designed to manage these modes to be separately worked, at each instant of time. The referenced commands in the form of the Euler and the corresponding quaternion are provided through $Ref - com$ and also the disturbances and the uncertainties are provided through $Dis - Unc$, where these ones to be considered through Monte-Carlo based representation.

In engine off mode to design $Quat - Cont$, the referenced commands should be presented in the form of quaternion vector information to be able to calculate the quaternion vector errors for the purpose of handling the outer loop proportional derivative control approach under the coefficients of $k_{p,dx}, k_{p,dy}$ and $k_{p,dz}$ in line with T thruster's level and by the following

$$\begin{pmatrix} \tau_x \\ \tau_y \\ \tau_z \end{pmatrix} = \begin{pmatrix} -T(k_{px}\, q_{1e} + k_{dx}\, \omega_x) \\ -T(k_{py}\, q_{2e} + k_{dy}\, \omega_y) \\ -T(k_{pz}\, q_{3e} + k_{dz}\, \omega_z) \end{pmatrix} \quad (8)$$

And the quaternion errors are taken as

$$\begin{bmatrix} q_{1e} \\ q_{2e} \\ q_{3e} \\ q_{4e} \end{bmatrix} = \begin{bmatrix} q_{4ref} & q_{3ref} & -q_{2ref} & -q_{1ref} \\ -q_{3ref} & q_{4ref} & q_{1ref} & -q_{2ref} \\ q_{2ref} & -q_{1ref} & q_{4ref} & -q_{3ref} \\ q_{1ref} & q_{2ref} & q_{3ref} & q_{4ref} \end{bmatrix} \begin{bmatrix} q_{1s} \\ q_{2s} \\ q_{3s} \\ q_{4s} \end{bmatrix} \quad (9)$$

where q_{iref} and q_{is}; $i = 1,2,3,4$ denote i^{th} referenced and system quaternion. In engine on mode to design $Eul - Cont$, the outer loops are dealt with via proportional integral derivative control approach,. The three-axis disturbances are inspired of the following

$$\tau_{dis} = L \times F\, DCM(Rt_{mis}) \quad (10)$$

It is to note that DCM indicate the direction cosine matrix and $L = r + \Delta c_g$ is assumed, at each instant of time, where r and Δc_g are related to engine arm and of the center of mass variation, respectively. Hereinafter, F and Rt_{mis} denote thrust vector and engine misalignments, as well.

3. Results and Discussion

There are two experiments with high and low thrusters regarding the engine off and on modes control to be discussed. It should be noted that the low thrusters are also considered by 25 N and 150 N, where the high thrusters are considered by 300 N and 600 N, respectively. It is to note that the profiles of the system parameters uncertainties are instantly updated along with Monte-Carlo based method between 0.9 and 1.2. Now, the moments of inertia is initially taken as

$$\begin{cases} I_x = 22.63 \\ I_y = 93.71 \\ I_z = 96.15 \end{cases} \quad (11)$$

And the three-axis engine arm is initially taken as $r = [-0.1,0,0]^T$. In one such case, the initial parameters, in engine off and on modes, are tabulated in Table 1.

Table 1. The initial parameters of the proposed control approach in engine off and on modes.

	The parameters	The values
1	Low thrust three-axis control coefficients in the outer loop	$\begin{cases} k_{pxyz} = 72 \\ k_{dxyz} = 200 \\ k_{ixyz} = 0 \end{cases}$
2	Low thrust three-axis control coefficients in the inner loop	$k_{pxyz} = 15.0$
3	High thrust y,z-axis control coefficients in the outer loop	$\begin{cases} k_{ix} = 0 \\ k_{iy} = 15262.5; \\ k_{iz} = 8547 \end{cases} \begin{cases} k_{dx} = 0 \\ k_{dy} = 0 ; \\ k_{dz} = 0 \end{cases} \begin{cases} k_{px} = 0 \\ k_{py} = 18315 \\ k_{pz} = 29792.4 \end{cases}$
4	Low thrust x-axis control coefficients in the outer loop	$\begin{cases} k_{ix} = 1000 \\ k_{iy} = 0 \\ k_{iz} = 0 \end{cases} ; \begin{cases} k_{dx} = 2621 \\ k_{dy} = 0 \\ k_{dz} = 0 \end{cases} ; \begin{cases} k_{px} = 443 \\ k_{py} = 0 \\ k_{pz} = 0 \end{cases}$
5	Low thrust x-axis control coefficients in the inner loop	$k_{px} = 15.0$
6	High thrust y,z-axis control coefficients in the inner loop	$\begin{cases} k_{px} = 0 \\ k_{py} = 6010.47 \\ k_{pz} = 5000 \end{cases}$

It is to note that the investigated results in the low and high thruster's dynamics to guarantee the system performance in the presence of the lower and upper band of uncertainties are tabulated in Table 2. Additionally, the three-axis steady state errors that are acquired through the proposed control approach, in engine on mode, is illustrated in Fig. 2. It is shown that the rise time of dynamics of the high thrusters is taken as about 70 ms and also the levels of the low thruster and the corresponding high thrusters are taken as 100 N-150 N and 400 N-600 N, respectively. In this regard, the investigated outcomes are acquired in a number of separated parameters uncertainties, where one of the case is only illustrated in the aforementioned outcome. Finally, the three-axis referenced commands tracking errors in engine off mode is illustrated in Fig. 3. All in all, the investigated results discussed indicate that the proposed comprehensive cascade is well behaved and the new insights are made to be presented.

Table 2. The low and high thruster's dynamics to guarantee the system performance in the presence of the lower and upper band of uncertainties.

	The steady state errors (deg.)			The low thruster's level (N)	The high thruster's level (N)	The lower and upper band of uncertainties (in percentage)	The system rise time (ms)
	z-axis	y-axis	x-axis				
1	5	0.5	8	100	400	90	69
2	12	1.5	12	150	600	120	69

Fig. 2. The three-axis steady state errors in engine on mode.

Fig. 3. The three-axis steady state errors in engine off mode.

4. Summary

The research proposed here is organized based upon the realization of double closed loop to deal with the rotational angles and its rates, while a number of propellant engine modes including on and off are taken into consideration. It is shown that the off mode is handled through quaternion based control approach, as long as the corresponding on mode is handled through Euler based control approach, while the disturbances and the uncertainties are provided in the process of analyzing the investigated outcomes. The present system parameters uncertainties are analyzed through Monte-Carlo based representation to verify the approach performance. A series of experiments are correspondingly carried out to present the investigated outcomes.

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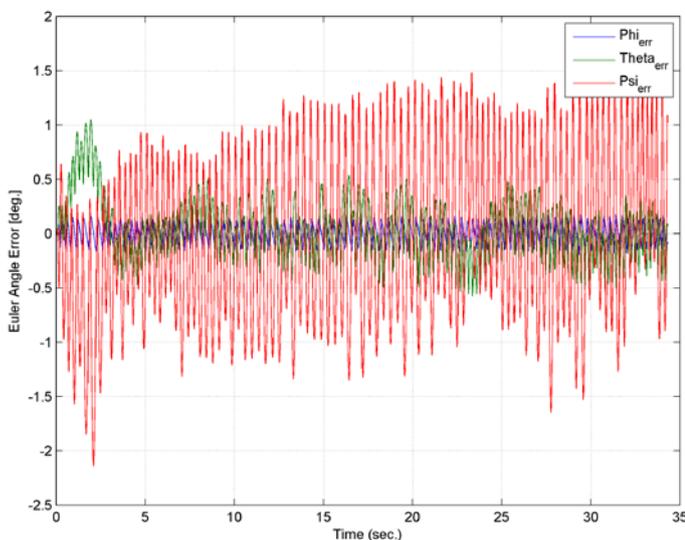
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