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Adaptive OutPut Feedback Attitude Control of a LEO Satellite Under Angular Velocity Constraints

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Abstract—**In this paper an adaptive output feedback control law is proposed for attitude control of a rigid spacecraft under a-priori known angular velocity constraints. The multiple model and switching approach is employed to improve the transient response of the control system in the case of large uncertainty in parameter space of the inertia matrix. Rigorous stability analysis for the proposed control law in the non-switching case is presented. An orbit and attitude simulator for a LEO satellite is developed and used to evaluate the proposed control scheme. The reported results show the effectiveness of the introduced scheme.**

Keywords-adaptive control; satellite attitude control; multiple model; passivity-based output feedback

I. INTRODUCTION

Satellites have such a significant role in today's life that we almost cannot imagine our everyday life without satellites services. The mission of a satellite and a space project in general, relies on its payload and the performance of most of common payloads in space projects is tightly related to the performance of the Attitude Control System (ACS). The ACS is responsible for reorienting the spacecraft to achieve desired orientation or attitude and counteract various disturbances present in the space environment.

The attitude control problem is also of great interest in areas other than space projects like aerial vehicles, robotics systems and submarine vehicles and there have been vast amounts of research dealing with various aspects of this problem during past few decades. An example of a comprehensive reference on spacecraft attitude control could be [1], while an analytical treatment to the subject can be found in [2] and [3] is an application oriented book. An in-depth treatment of attitude determination is given in the [4]. A detailed list of references through 1991 is given in [5]. In this reference a feature inherent in quaternion for describing the configuration space of rigid body attitude motion that is double covering of the attitude space was pointed out. The consequent problems of this feature are the so-called unwinding phenomenon, the impossibility of globally stabilizing the attitude using a continuous controller which led to the introduction of "almost" global stability notion, the need for a path lifting mechanism and using sort of memory in control law. To be more specific, the state space of attitude motion; SO(3), which is the set of all orthogonal 3×3 matrices with determinant 1, is a boundaryless compact manifold and is not a vector space. On the other hand quaternion representation of attitude is the set of all vectors in $\Re^4$ with unit magnitude and it double covers the set SO(3). These problems are now well understood and reported in [6,7] among others.

The problem of stabilizing spacecraft attitude has been considered for a long time by many researchers and there are a variety of proposed techniques such as [8,9] to cite main works. In these works a PD-like controller with a linear structure is used. The proportional term includes a measure of attitude error [5], while the derivative term uses angular velocity for damping purposes. Various output feedback controllers have been also proposed; In contrast to [10] which uses dynamic observer to establish output feedback, [11] proposed a passivity-based lead filter to generate pseudo-velocities to be used in control law. This approach which thereafter was also incorporated in many works such as [12, 13], though eliminates the direct use of angular velocity in control law; as there does not exist any device to measure the attitude directly, the need for angular velocity measurement might not be eliminated. A finite time state observer together with a finite time control law in terms of MRPs has been proposed in [14] that constitute a finite time output feedback attitude control scheme. This scheme is also applicable to a more general class of second order nonlinear systems. The stability analysis for both observer and control law is also presented.

Adaptive attitude control seems to have great potential for satisfying spacecraft attitude control problem requirements. A wide class of adaptive control schemes has been proposed. In [15], an adaptive trajectory tracking controller is presented for a large class of nonlinear mechanical systems especially the rigid body attitude control problem. An adaptive attitude controller subject to constraints on angular velocity is proposed in [16]. In this control law the constraints on angular velocity components are explicitly used in the controller formulation. In [17] a model reference adaptive controller is developed for spacecraft rendezvous and docking problem. In this work a passivity based lead filter similar to that of [13] is used to achieve output feedback control.

All of the abovementioned adaptive controllers are based on certainty-equivalence principle; in turn, they consider a deterministic control law and combine it with an appropriate parameter adaptation law to achieve an adaptive control law. The resulting closed loop system is nonlinear time-varying and due to parameter adaptation apart from the actual values has inferior performance to the deterministic case. A popular and general solution to overcome the drawbacks of classical adaptive control which we adopted in this work is the multiple model and switching approach. In classical adaptive control the plant is supposed to have unknown constant parameters and because of this in the case of abrupt change or large uncertainty in the parameters, classical adaptive control leads to a poor performance especially from a transient response point of view. As a solution to these problems, multiple model and switching approach attracted interests from the early ages of adaptive control. Implementation of this approach is presented in [18] for the aircraft flight control problem. Multiple model adaptive control with switching and tuning with stability proof for special cases is introduced in [19]. In [20], the authors try to give a methodology for designing multiple model adaptive controllers that guarantee a superior performance and stability properties in comparison with the best non-adaptive controllers.

The proposed method in this paper is adopted from [22] which uses a number of models and provides an estimate of the plant parameter which depends on the collective outputs of all the models. Our focus in this paper is on attitude control under angular velocity constraints, since in spite of its practical applications there is much lower works on it than other problems in attitude control. Angular velocity constraints may be occurred in the cases such as low-rate gyros, in-flight refueling, spacecraft docking etc. In [23], an integrator back-stepping technique for a dynamical system under angular velocity constraint is proposed and a Lyapunov function including a logarithmic term is introduced to deal with angular velocity bounds. In [24], a nonlinear controller with actuator and slew rate saturation is introduced.

The contribution of this work is threefold. First, almost global asymptotic stability of a control law for attitude control under angular velocity constrains is rigorously proved. Second, the output feedback variant of this control law is presented and third, the transient response of the proposed control law is significantly improved exploiting multiple model approach. This paper is organized as follows. In Section 2 the mathematical model of spacecraft attitude is stated. The proposed multiple model adaptive attitude control is presented in Section 3 and Section 4 demonstrates simulation results. Finally we conclude the paper in Section 5 and some future study issues are stated.

II. Mathematical Model of Spacecraft Attitude

In this section the mathematical model of a rigid spacecraft is introduced. This model consists of spacecraft dynamics and its kinematics equation. Dynamics equation is described by the well-known Euler's moment equation and it concerns the act of torques on the rigid body rotational motion. Kinematics equation describes relationship between velocity and position-related quantities (attitude in rotational motion) regardless of torques acting on the body. While there are many representations for the attitude of a rigid body quaternions are most common since they are singularity-free and lead to a linear kinematics equation.

The quaternion vector representing the attitude of body frame with respect to inertial frame is introduced as

$$\mathbf{q} = \begin{bmatrix} \mathbf{q}_{1:3} \\ q_4 \end{bmatrix}, \tag{1}$$

where $\mathbf{q}_{1:3}$ is the vector part and q_4 is the scalar part of the quaternion vector. Kinematics of a rigid body is given by the following equation [4]

$$\dot{\mathbf{q}} = \frac{1}{2}\mathbf{\Omega}(\boldsymbol{\omega})\mathbf{q}, \tag{2}$$

where $\boldsymbol{\omega}$ is the angular velocity of body frame with respect to inertial frame expressed in the body frame and

$$\mathbf{\Omega}(\boldsymbol{\omega}) = \begin{bmatrix} 0 & \omega_3 & -\omega_2 & \omega_1 \\ -\omega_3 & 0 & \omega_1 & \omega_2 \\ \omega_2 & -\omega_1 & 0 & \omega_3 \\ -\omega_1 & -\omega_2 & -\omega_3 & 0 \end{bmatrix}. \tag{3}$$

Euler's moment equation gives the nonlinear three-axis dynamics equation of a rigid body as:

$$\mathbf{I}\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega}\times\mathbf{I}\boldsymbol{\omega} + \boldsymbol{u}, \tag{4}$$

where $\mathbf{I} \in \Re^{3\times 3}$ is the symmetric positive definite inertia matrix of the rigid body, $\boldsymbol{u} \in \Re^3$ is the control input, and $\times$ denotes cross product operation.

III. Multiple Model Adaptive output feedback Attitude Controller

In this section the proposed multiple model adaptive output feedback attitude control scheme is described. First we introduce a modified variant of adaptive control law presented in [16], which explicitly takes into account angular velocity bounds. We eliminate the need for direct angular velocity measurement using passivity based lead filter, then we use the resulting control law as a core controller and improve its transient response using multiple model and switching approach to adaptive control.

Let $\mathbf{q}$ be the instantaneous attitude quaternion of the spacecraft and $\bar{\mathbf{q}}$ be the desired attitude quaternion. The attitude error in terms of quaternion is defined as [4],

$$\delta\mathbf{q} \equiv \begin{bmatrix} \delta\mathbf{q}_{1:3} \\ \delta q_4 \end{bmatrix} = \mathbf{q}\otimes\bar{\mathbf{q}}^{-1} = \begin{bmatrix} \Xi(\bar{\mathbf{q}}^{-1}) & \bar{\mathbf{q}}^{-1} \end{bmatrix}\mathbf{q}, \tag{5}$$

where,

$$\Xi(\bar{\mathbf{q}}^{-1}) = \begin{bmatrix} \bar{q}_4 & \bar{q}_3 & -\bar{q}_2 \\ -\bar{q}_3 & \bar{q}_4 & \bar{q}_1 \\ \bar{q}_2 & -\bar{q}_1 & \bar{q}_4 \\ \bar{q}_1 & \bar{q}_2 & \bar{q}_3 \end{bmatrix}. \tag{6}$$

Let the constraints on angular velocity components be described as follows

$$|\omega_1(t)| \le k_1, |\omega_2(t)| \le k_2, |\omega_3(t)| \le k_3. \tag{7}$$

The main adaptive output feedback control law is proposed as

$$\boldsymbol{u} = -\mathbf{I}\mathbf{K}_v^{-1}(\delta\mathbf{q}_{1:3} + k_5\mathbf{v}), \tag{8}$$

where, $\mathbf{v} = [v_1 \quad v_2 \quad v_3]^T$ is the synthesized angular velocity to be introduced later, and

$$\mathbf{K}_v = \begin{bmatrix} \frac{k_4}{k_1^2 - v_1^2} & 0 & 0 \\ 0 & \frac{k_4}{k_2^2 - v_2^2} & 0 \\ 0 & 0 & \frac{k_4}{k_3^2 - v_3^2} \end{bmatrix}, \tag{9}$$

and $\mathbf{I}$ is the inertia matrix.

One advantage of control law (8) lies in the fact that it is an output feedback control law, i.e. there is no need to measure angular velocity of the rigid spacecraft and this is achieved by using the synthesized angular velocity instead of measured angular velocity. We follow a procedure similar to that presented in [11] to construct synthesized angular velocity. The synthesized angular velocity is defined as

$$\mathbf{v} = 2\Xi^T(\delta\mathbf{q})z, \tag{15}$$

where, $\mathbf{z}$ is obtained by passing $\delta\dot{\mathbf{q}}$ through an LTI strictly proper and strictly positive real system $\mathbf{C}(s)$

$$z = \mathbf{C}(s)\delta\dot{\mathbf{q}}. \tag{16}$$

To design and implement this filter consider a minimal realization of $\mathbf{C}(s)$ as

$$\dot{\xi} = \boldsymbol{A}\xi + \boldsymbol{B}\delta\dot{\mathbf{q}}; \quad z = \boldsymbol{C}\xi. \tag{17}$$

since $\mathbf{C}(s)$ is strictly positive real and strictly proper, the Kalman-Yakubovich-Popov's Lemma implies that there exist positive definite matrices $\boldsymbol{P}$ and $\boldsymbol{Q}$ such that

$$\boldsymbol{A}^T\boldsymbol{P} + \boldsymbol{P}\boldsymbol{A} = -\boldsymbol{Q}; \quad \boldsymbol{P}\boldsymbol{B} = \boldsymbol{C}^T, \tag{18}$$

and (15) is implementable by choosing any Hurwitz matrix $\boldsymbol{A}$, full column rank matrix $\boldsymbol{B}$ and positive definite matrix $\boldsymbol{Q}$. Rewrite (17) as

$$\begin{aligned} \dot{\xi}_1 &= \boldsymbol{A}\xi_1 + \boldsymbol{B}\delta\mathbf{q} \\ z &= \boldsymbol{C}\dot{\xi}_1 = \boldsymbol{B}^T\boldsymbol{P}(\boldsymbol{A}\xi_1 + \boldsymbol{B}\delta\mathbf{q}) \end{aligned}. \tag{19}$$

the above results are summarized in the following theorem and the rigorous stability analysis is presented.

Theorem: the control law (8) almost globally stabilizes the system described by (2) and (4).

Proof: equation of the closed loop system is

$$\mathbf{I}\dot{\boldsymbol{\omega}} = -[\boldsymbol{\omega}\times]\mathbf{I}\boldsymbol{\omega} - \mathbf{I}\mathbf{K}_v^{-1}(\delta\mathbf{q}_{1:3} + k_5\boldsymbol{\omega}). \tag{20}$$

the equilibrium points of this system are

$$(\delta\mathbf{q}, \boldsymbol{\omega}) = ([\delta\mathbf{q}_{1:3}; \delta q_4], \boldsymbol{\omega}) = ([0; \pm 1], 0) \tag{21}$$

both of these equilibrium points are associated with one physical attitude. Consider the Lyapunov function

$$V = (1 - \delta q_4)^2 + \delta\mathbf{q}_{1:3}^T\delta\mathbf{q}_{1:3} + \frac{1}{2}k_4\sum_{i=1}^{3}\ln\frac{k_i^2}{k_i^2 - \omega_i^2} > 0 \tag{22}$$

The first two terms in this Lyapunov function are a measure of potential energy of the rigid body w.r.t reference attitude and the logarithmic term was first proposed in [23] to treat constraints on the angular velocity. Taking time derivative of this Lyapunov function yields

$$\dot{V} = -2(1 - \delta q_4)\delta\dot{q}_4 + 2\delta\mathbf{q}_{1:3}^T\delta\dot{\mathbf{q}}_{1:3} + \boldsymbol{\omega}^T\mathbf{K}_\omega\dot{\boldsymbol{\omega}} \tag{23}$$

by Substituting for $\delta\dot{\mathbf{q}}$ and $\dot{\boldsymbol{\omega}}$, (23) reduces to

$$\dot{V} = -k_5\boldsymbol{\omega}^T\boldsymbol{\omega} - \boldsymbol{\omega}^T\mathbf{K}_\omega\mathbf{I}^{-1}[\boldsymbol{\omega}\times]\mathbf{I}\boldsymbol{\omega} \tag{24}$$

for investigating the sign of $\dot{V}$ let define

$$\mathbf{G} = \mathbf{K}_\omega\mathbf{I}^{-1}[\boldsymbol{\omega}\times]\mathbf{I} \tag{25}$$

which leads to

$$\dot{V} = -k_5\boldsymbol{\omega}^T\boldsymbol{\omega} - \boldsymbol{\omega}^T\mathbf{G}\boldsymbol{\omega} \tag{26}$$

let the upper bound on the Euclidean norm of $\mathbf{G}$ be known as

$$\mathbf{G} < g \tag{27}$$

then choosing $k_5 > g$ leads to

$$\dot{V} \le 0 \tag{28}$$

i.e. $\dot{V}$ is negative semi definite And hence the equilibrium points $([0; \pm 1], 0)$ are stable. To prove asymptotic stability we use Lasalle theorem. As the system is stable it yields that $\delta\mathbf{q}, \boldsymbol{\omega} \in \mathbf{L}_\infty$. Taking integral of both sides of equation (26) (e.g. for $k_5 = g + 1, G = g$) yields $\boldsymbol{\omega} \in \mathbf{L}_2$ and hence $\boldsymbol{\omega} \in \mathbf{L}_\infty \cap \mathbf{L}_2$. Then by using Barbalat's Lemma we have $\lim_{t\to\infty}\boldsymbol{\omega} = 0$. The equation of closed loop system (20) shows that $\lim_{t\to\infty}\boldsymbol{\omega} = 0$ only if $\lim_{t\to\infty}\delta\mathbf{q}_{1:3} = 0$. Hence the largest invariant subset in $\Omega = \{(\delta\mathbf{q}, \boldsymbol{\omega}) | \dot{V}(x) = 0\}$ is $\{([\delta\mathbf{q}_{1:3}; \delta q_4], \boldsymbol{\omega}) = ([0; 1], 0)\}$. So the asymptotic stability is proved by Lasalle theorem.

We mention that the proposed attitude control law does not guarantee the shortest path to be travelled. The stability analysis in [16] is not rigorous as claimed, e.g. it is not mentioned whether the controller globally stabilizes the system or not. This seems to be because of the abovementioned ambiguity in stability analysis of control systems in terms of quaternion coordinate.

The next step is to apply multiple model and switching approach to the main control law (8). Usually there are two possibilities for generating model bank in multiple model adaptive control. First one is generating models based on system dynamics described in various coordinates or models obtained by different simplification methods. Second method keeps one governing dynamics equation and establishes models by dividing parameter space of the plant. In this paper we adopted the latter and consider parameter space of inertia matrix $\mathbf{I} \in \Re^{3\times3}$. Since the inertia matrix is symmetric the parameter space is

$$\boldsymbol{S} = \left\{ \boldsymbol{\theta} \in \Re^6 \middle| \mathbf{I} \succ 0, \ell_i \le \theta_i \le u_i, i = 1,2,\ldots,6 \right\}, \tag{29}$$

where the constraints $\ell_i \le \theta_i \le u_i, i = 1,2,\ldots,6$ are based on a priori knowledge of inertia matrix entries. This parameter space is broken to N subspaces by considering N initial choices for the inertia matrix in main adaptive law. The choice of the value of N depends on the trade-off between desire performance and controller complexity made by the designer. The actual inertia matrix and other initial choices are named as $\mathbf{I}_p$: actual inertia matrix of the spacecraft; $\mathbf{I}_i, i = 1,2,\ldots,N$: inertia matrix choices with different amounts of uncertainty corresponding to different subspaces in $\boldsymbol{S}$.

The structure of the proposed multiple model adaptive attitude control is shown in Fig. 1. In this figure N identification models are constructed by the N initial choices for inertia matrix using the parameter adaptation law (11), and spacecraft attitude dynamics and kinematics equations (2) and (4).

In multiple model adaptive control, switching mechanism is an essential part which determines active controller at every instance based on some measured signals and identified models. The proposed switching mechanism selects the nearest model-controller pair to the actual plant based on the fallowing criteria

$$\text{active controller index} = \underset{i=1,2,\ldots,N}{\operatorname{argmin}} \left\| \mathbf{q}_p - \mathbf{q}_i \right\|_2 . \tag{30}$$

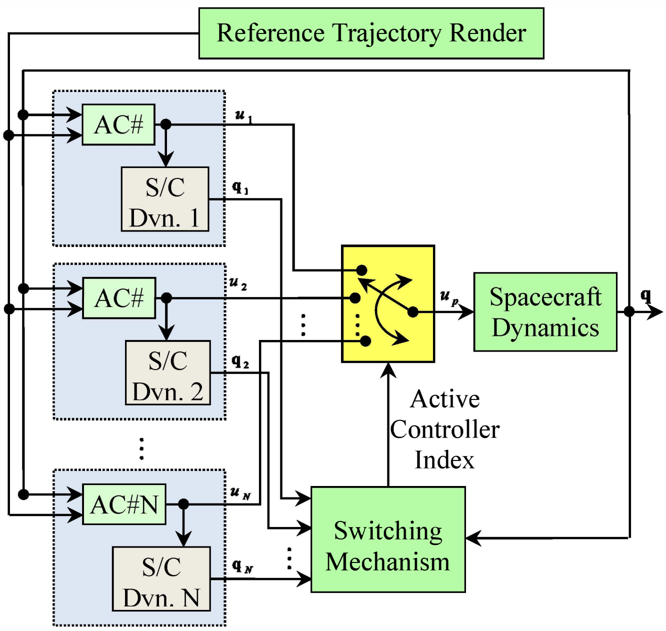

Figure 1. Structure of Multiple Model Adaptive Attitude Controller

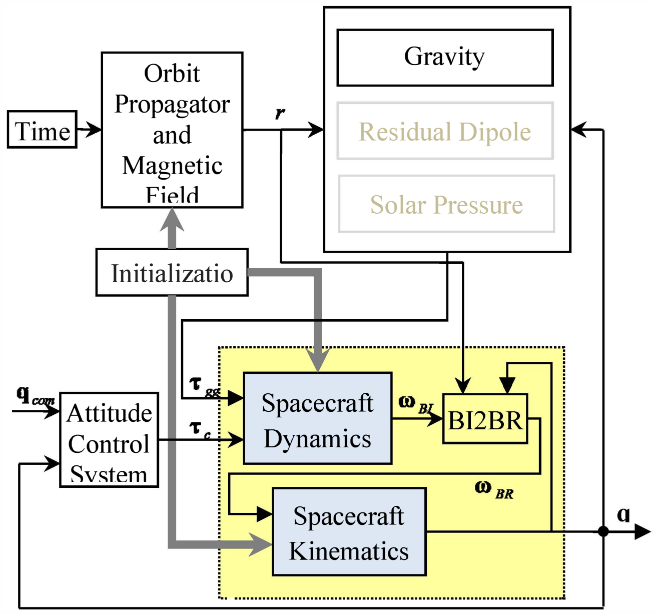

Figure 2. Block Diagram of the Compact LEO Satellite Attitude Simulator

IV. Simulation Results on a LEO Satellite Simulator

In this section the simulation results for the proposed control schemes are reported. An attitude and orbit simulator for a LEO satellite is developed. Fig. 2 illustrates this simulator. For the sake of brevity the details of this simulator are not presented here.

We consider $N = 2$ which means we have two identification models. For evaluating performance of the proposed control scheme we consider regulating the spacecraft attitude to a fixed commanded attitude. The values of parameters used in simulation are given in Table 1.

Simulation results for both, the pure adaptive control and the multiple model adaptive control are shown in Figs. 3-7. Fig. 3 shows quaternion behavior for the pure adaptive control and Fig. 5 shows that of multiple model control. Although in both cases the quaternion vector converges to the commanded quaternion, the performance improvement due to incorporating multiple model approach can be clearly seen in Fig. 5. Since Euler angles are more intuitive appropriate transformation is used and system response in terms of Euler angles is also shown in Fig. 4 and Fig. 6 for both control schemes.

Fig. 7 shows the time histories of switching between two controllers. For the proposed switching logic, switching between controllers will not stop even after convergence to the commanded quaternion. This may in part be because of disturbance effect and hence one could invoke sort of feed-forward terms in control law to avoid unwanted switching. Modifying the switching logic by insertion of dwell time or hysteresis is also possible.

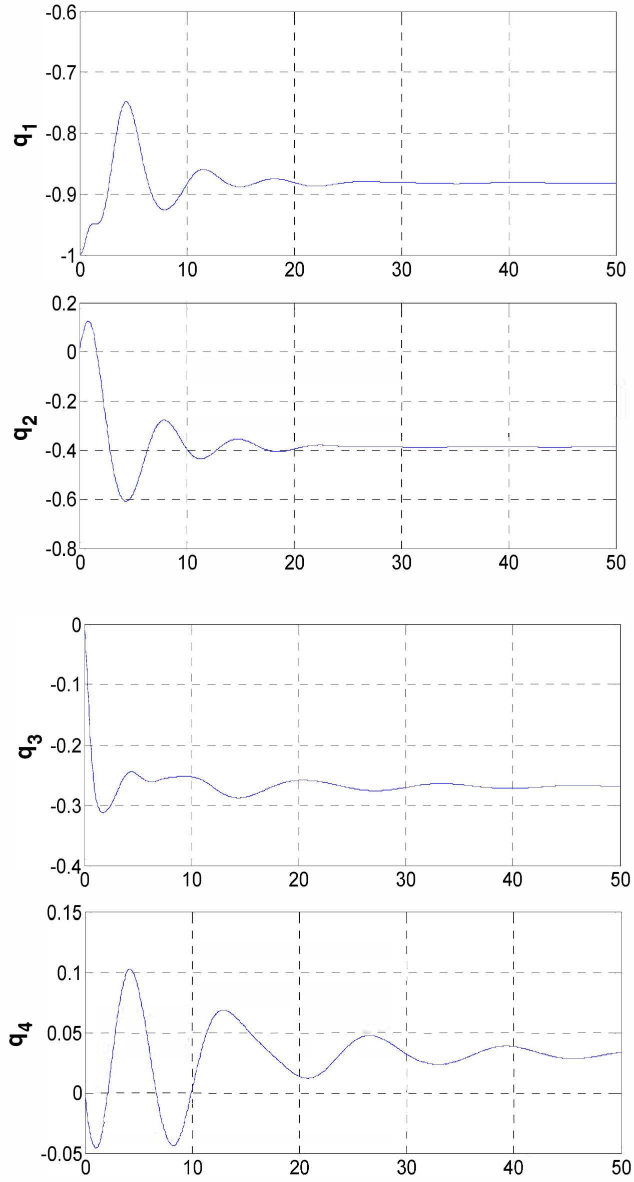

Figure 3. Quaternion vector vs time (seconds) for pure adaptive controller

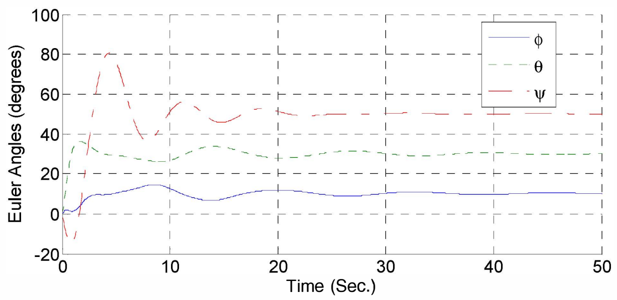

Figure 4. Euler Angles step response for pure adaptive controller

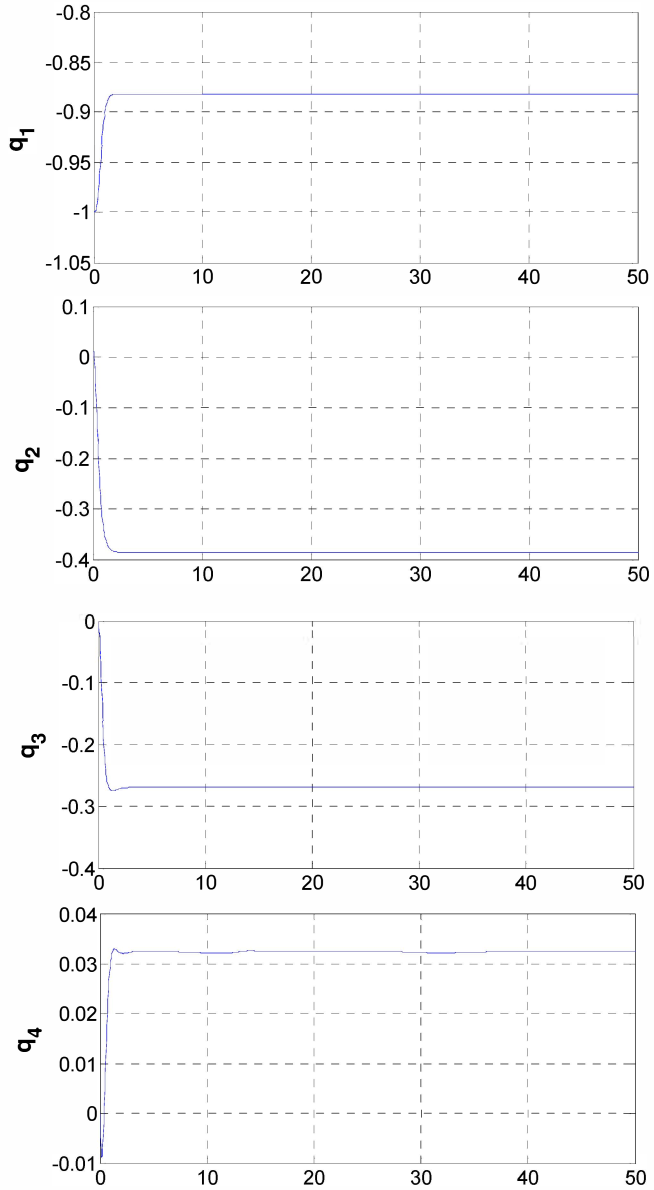

Figure 5. Quaternion vs time (seconds) for multiple model adaptive controller

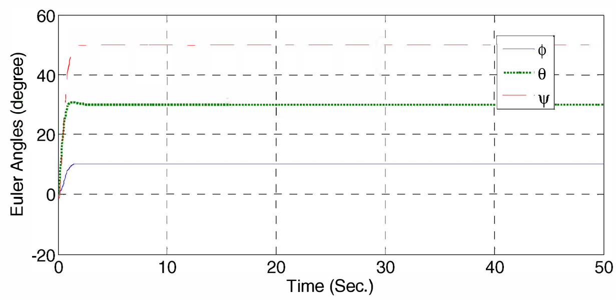

Figure 6. Euler Angles step response for multiple model adaptive controller

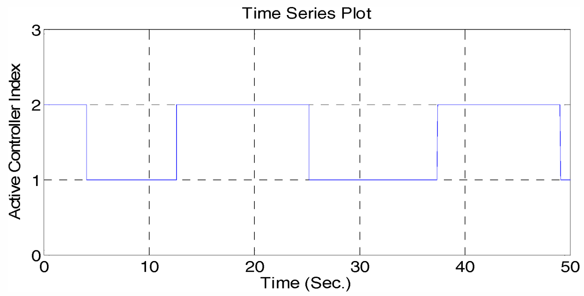

Figure 7. Active controller index in multiple model control

TABLE I. VALUES OF SIMULATION PARAMETERS

Parameter		Value
Orbit Parameters	Height	800 Km
	Inclination	$\pi / 3$ rad
	Right ascension	0
	Arg. of Perigee	0
	Mean anomaly	0
Satellite Actual Inertia Matrix		$\mathbf{I} = [300, 50, 20; 50, 110, 0; 20, 0, 800]$
Controller 1 Initial Inertia Matrix		$\mathbf{I} = [15, 3, 2; 3, 50, 4; 2, 4, 14]$
Controller 2 Initial Inertia Matrix		$\mathbf{I} = [250, 30, 20; 30, 90, 4; 20, 4, 500]$
Constant Gains of main Controller	k_1	80
	k_2	80
	k_3	80
	k_4	200
	k_5	0.8
	$\mathbf{\Gamma}$	$0.05 \times eye(6)$
Lead Filter Realization	**A**	$-30 \times eye(4)$
	B	$33 \times eye(4)$
	Q	$30 \times eye(4)$
	C	$16.5 \times eye(4)$
Initial quaternion		$(0, 0, 0, -1)$
Commanded quaternion		$(-0.2448, -0.1821, -0.3676, -0.8785)$
Initial Euler Angles		$(0, 0, 0)$ degrees
Commanded Euler Angles		$(10, 30, 50)$ degrees

V. CONCLUSION

In this work, an adaptive passivity-based output feedback control law is proposed for satellite attitude control under angular velocity constraints and it's almost global asymptotic stability is proved using Lyapunov second method. The transient response of this control law in the regulation problem was improved significantly by applying the multiple model and switching approach to adaptive control. In particular the multiple model and switching approach was achieved by dividing the parameter space of inertia matrix to smaller subspaces. A LEO satellite attitude and orbit simulator was developed and used for evaluation of the proposed control scheme. Future works includes investigation of robustness of control law (8) against bounded time variant external disturbances and reconsidering the same problem taking into account actuator saturation.

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