A Novel Mechanical Attitude Simulator with Adaptive Control for Micro-Satellite

M. Kabganian, R. Nadafi, Y. Tamhidi, and M. Bagheri

***Abstract* — A novel simulator of satellite ADCS (Attitude Determination and Control System) was designed in the system dynamics and control research laboratory of Amirkabir University of Technology (Tehran Polytechnic). Currently, industrial models of ADCS are using air bearings to make the system suspended. A prototype was designed with ball bearings and three gimbals to provide three rotational DOFs. We believe that the advantages of our method are that is cost efficiency, improved the accuracy and performance; however, the model uses a high-level algorithm for friction compensation. The attitude accuracy of the system is nearly 5 degrees. The goal of this project is tracking and control of the ADCS in conditions in which the friction torque of the ball bearings in gimbals has been compensated. The controller implemented in this system uses a nonlinear model based on adaptive control. First, feedback linearization is used to cancel the nonlinearities which then was modified by an adaptive control using a Lyapunov function to estimate the uncertainties such as moments of inertia, the eccentricity of the center of mass, and friction. The friction model includes Stribeck, viscous, and Coulomb terms. High-level estimators and identifiers are used for estimation and identification of friction model parameters. Finally, the controllers were validated by simulation results.**

Keywords: adaptive control, friction, estimation, ADCS, Lyapunov function, ball bearing

I. INTRODUCTION

One of the important subsystems of a satellite is ADCS. Every attitude maneuver of a satellite is accomplished under the supervision of this system. This highly complex system utilizes multiple actuators such as reaction wheels, control moment gyroscope, magnetorquer, and thruster. ADCS also has different sensors with different applications such as sun sensor, star sensor, and earth sensor [1]. All of the subsystems of a satellite should be simulated on earth before it is placed in its orbit. ADCS is not an exception and it should have a simulator. The complete model of this simulator has three DOFs. Simulations have been carried out by using different models of ADCS simulator. Some of these models are tabletop, umbrella, planar, and dumbbell type [2]. These simulators utilize air bearings. Air bearing provides unconstrained movement in three DOFs. These air bearings could be spherical or semispherical. The high-level technologies are necessary to manufacture air bearings. Tolerances and clearances are very important in air bearings. They should have additional equipment to control and provide the appropriate air pressure. They are very expensive and they make noise because of air flow. Also, their maintenance is so important because of the sensitivity to air pollution.

A novel 3-DOF ADCS simulator was designed in the *System Dynamics and Control Research Laboratory* of the mechanical engineering department of Amirkabir University of Technology (Tehran Polytechnic). Considering the small value of the required accuracy (5 degrees) and some other limitations, three gimbals were used instead of air bearings. Each of these gimbals corresponds to one of the Euler angles. One of the problems associated with ordinary gimbals is that they could result in gimbals lock. It should be mentioned that the novel simulator proposed in this research never faces gimbals locking because the gimbals cannot become coaxial.

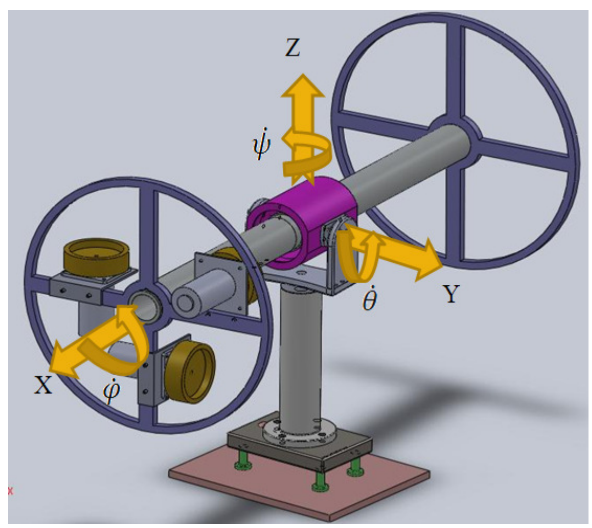

Figure 1. Micro-satellite simulator (the gimbals and motors are represented)

Another important factor is high friction torque in each gimbal. This should also be compensated to ensure the free floating condition of the simulator.

Each encoder measures one of the Euler angles. The simulator mimes the dumbbell type. Three reaction wheels were placed at one side of the simulator and batteries and motor driver circuits were put at the other side to counterbalance the weight. Some parameter uncertainties

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associated with our model are the eccentricity of the center of mass, friction, angular momentums, and moments of inertia. The friction model torque includes Stribeck, viscous, and Coulomb terms. Nonlinear and model-based controllers such as adaptive controller were put into practice to overcome these uncertainties. In what follows, equations of motion of the microsatellite simulator are derived first. Then friction is modeled and added to the system. Finally, simulation results of this adaptive control (based on the Lyapunov function) are presented.

II. DYNAMIC MODELING OF THE SIMULATOR

The simulator attitude dynamic equations is [3]

$$\boldsymbol{H}\dot{\boldsymbol{\omega}} = \boldsymbol{P} \times \boldsymbol{\omega} + \boldsymbol{\tau} \tag{1}$$

where ω is the solid body angular velocity, H is the moment of inertia of whole of the simulator (it includes the moment of inertia of the each reaction wheels), P is the angular momentum of solid movement of the simulator, and τ is the external torque that includes the variation of the angular momentum of reaction wheels. This torque is given by:

$$\begin{aligned} &-([\boldsymbol{I}_{rw1}]\dot{\boldsymbol{\omega}}_{rel1} + [\boldsymbol{I}_{rw2}]\dot{\boldsymbol{\omega}}_{rel2} + [\boldsymbol{I}_{rw3}]\dot{\boldsymbol{\omega}}_{rel3}) \\ &-\boldsymbol{\omega} \times ([\boldsymbol{I}_{rw1}]\boldsymbol{\omega}_{rel1} + [\boldsymbol{I}_{rw2}]\boldsymbol{\omega}_{rel2} + [\boldsymbol{I}_{rw3}]\boldsymbol{\omega}_{rel3}) \\ &-\boldsymbol{f} = \boldsymbol{\tau} \end{aligned} \tag{2}$$

Where ω_{rel} is the relative angular velocity of the reaction wheels. It should be remembered that:

$$\boldsymbol{P}\times = \begin{bmatrix} 0 & -\boldsymbol{P}_3 & \boldsymbol{P}_2 \\ \boldsymbol{P}_3 & 0 & -\boldsymbol{P}_1 \\ -\boldsymbol{P}_2 & \boldsymbol{P}_1 & 0 \end{bmatrix} \tag{3}$$

Complete Stribeck friction model was used for the friction modeling [4].

$$f(V) = (F_C + (F_s - F_c)e^{(V/V_s)^2})\operatorname{sgn}(V) + \sigma V \tag{4}$$

Where F_C is Coulomb coefficient, F_s is Stribeck coefficient, σ is viscous coefficient, and V_s is Stribeck velocity.

According to the existence of V_s in the power of exponential term and making the friction nonlinear in parameters, we should implement the nonlinear identification method on the system. The result is $V_s = 0.01 m/s$. It should be denoted that the velocities in (4) are Euler angles differentiation.

There is a conversion between body angular velocity ω, and the differentiation of quaternion states[1].

$$\frac{d}{dt}\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} q_4 & -q_3 & q_2 \\ q_3 & q_4 & -q_1 \\ -q_2 & q_1 & q_4 \\ -q_1 & -q_2 & -q_3 \end{bmatrix}\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \tag{5}$$

So (5) can be rewritten as following:

$$\dot{\boldsymbol{X}} = \boldsymbol{J}(\boldsymbol{X})\boldsymbol{\omega} \tag{6}$$

The goal of this section is converting simulator dynamic equation to robotic one. So if $\tau = J^T F$ is used, and then the robotic equation is given by:

$$\boldsymbol{H}^*(\boldsymbol{X})\ddot{\boldsymbol{X}} + \boldsymbol{C}^*(\boldsymbol{X},\dot{\boldsymbol{X}})\dot{\boldsymbol{X}} + \boldsymbol{f}^*(\dot{\boldsymbol{X}}) = \boldsymbol{F} \tag{7}$$

So inertia, damping, and friction matrices could be represented by:

$$\begin{aligned} &\boldsymbol{H}^*(\boldsymbol{X}) = \boldsymbol{J}^{-T}\boldsymbol{H}\boldsymbol{J}^{-1} \\ &\boldsymbol{C}^*(\boldsymbol{X},\dot{\boldsymbol{X}}) = \boldsymbol{J}^{-T}\boldsymbol{H}\dot{\boldsymbol{J}}^{-1} - \boldsymbol{J}^{-T}[\boldsymbol{P}\times]\boldsymbol{J}^{-1} \\ &\boldsymbol{f}^*(\dot{\boldsymbol{X}}) = \boldsymbol{J}^{-T}\boldsymbol{f} \end{aligned} \tag{8}$$

III. ADAPTIVE CONTROL

The Lyapunov function candidate for adaptive control design is[3].

$$V = \frac{1}{2}[\boldsymbol{S}^T\boldsymbol{H}^*\boldsymbol{S} + \tilde{\boldsymbol{a}}^T\Gamma^{-1}\tilde{\boldsymbol{a}}] \tag{9}$$

The state error is defined as:

$$\tilde{\boldsymbol{X}} = \boldsymbol{X} - \boldsymbol{X}_d \tag{10}$$

In this Lyapunov function the below filter was used:

$$\boldsymbol{S} = \dot{\tilde{\boldsymbol{X}}} + \boldsymbol{\lambda}\tilde{\boldsymbol{X}} \tag{11}$$

Reference path is defined $\dot{\boldsymbol{X}}_r = \dot{\boldsymbol{X}}_d - \boldsymbol{\lambda}\tilde{\boldsymbol{X}}$. So S can be redefined as:

$$\boldsymbol{S} = \dot{\boldsymbol{X}} - \dot{\boldsymbol{X}}_r \tag{12}$$

In (9), $.\tilde{a} = \hat{a} - a$. is defined as parameters error. And also Γ is a positive definite matrix. After these definitions, differentiation of Lyapunov function is given by:

$$\dot{V} = \tilde{a}^T \Gamma^{-1} \dot{\tilde{a}} + S^T (F - f^* - H^* \ddot{X}_r - C^* \dot{X}_r) \quad (13)$$

The system control effort could be defined as:

$$F = \hat{H}^* \ddot{X}_r + \hat{C}^* \dot{X}_r + \hat{f}^* - K_D S \quad (14)$$

Where inertia, damping, and friction matrices error are as following:

$$\begin{aligned} \tilde{H}^* &= \hat{H}^* - H^* \\ \tilde{C}^* &= \hat{C}^* - C^* \\ \tilde{f}^* &= \hat{f}^* - f^* \end{aligned} \quad (15)$$

Finally, the result of differentiation of Lyapunov function is:

$$\begin{aligned} \dot{V} &= \tilde{a}^T \Gamma^{-1} \dot{\tilde{a}} - S^T K_D S \\ &+ S^T (\tilde{H}^* \ddot{X}_r + \tilde{C}^* \dot{X}_r + \tilde{f}^*) \end{aligned} \quad (16)$$

Below statement could be changed to the multiplication of a regressor matrix and vector of parameters error by linear parameterization.

$$\begin{aligned} &\tilde{H}^*(X)\ddot{X}_r + \tilde{C}^*(X, \dot{X})\dot{X}_r + \tilde{f}^*(\dot{X}) = \\ &Y^*(X, \dot{X}, \dot{X}_r, \ddot{X}_r)\tilde{a} \end{aligned} \quad (17)$$

Finally it can be written differentiation of Lyapunov function as following:

$$\dot{V} = -S^T K_D S + \tilde{a}^T [\Gamma^{-1} \dot{\tilde{a}} + Y^{*T} S] \quad (18)$$

The first term of right-hand terms is negative definite. So the second term could be taken zero and adaptation law could be concluded.

$$\dot{\hat{a}} = -\Gamma Y^{*T} S \quad (19)$$

Finally, torque control could be defined:

$$\begin{aligned} \tau &= J^T (\hat{H}^* \ddot{X}_r + \hat{C}^* \dot{X}_r + \hat{f} - K_D S) \\ &= J^T (Y^* \hat{a} - K_D S) \end{aligned} \quad (20)$$

IV. RESULT OF SIMULATION

In this part, control of dynamic equation of simulator (7) is represented by (20) and the convergence of parameters is shown by (18).

Vector of parameters are six moments of inertia of the simulator ($I = [I_{xx}; I_{xy}; I_{xz}; I_{yz}; I_{zz}]$), three angular momentum ($P = [P_1; P_2; P_3]$) and nine friction parameters

$$fp = [F_{C1}; F_{S1} - F_{C1}; \sigma_1; F_{C2}; F_{S2} - F_{C2}; \sigma_2; F_{C3}; F_{S3} - F_{C3}; \sigma_3].$$

It should be mentioned that angular velocities are chosen as parameters because of their low variation and low angular velocity of the simulator. These parameters have the real values as follows.

TABLE I. The real values of the parameters

Name of The Parameters	Real Value of Parameters	Unit
I_{xx}	0.3380	$Kg.m^2$
I_{xy}	0.0013	$Kg.m^2$
I_{xz}	-0.00012	$Kg.m^2$
I_{yy}	0.3389	$Kg.m^2$
I_{yz}	-0.0034	$Kg.m^2$
I_{zz}	0.03278	$Kg.m^2$
F_{C1}	0.2	N
F_{s1}	0.12	N
σ_1	0.001	$N.s/m$
F_{C2}	0.1	N
F_{s2}	0.06	N
σ_2	0.005	$N.s/m$
F_{C3}	0.1	N
F_{s3}	0.06	N
σ_3	0.005	$N.s/m$

In this part convergence of the error of the quaternion parameters, uncertain parameters, control effort and desired path are shown.

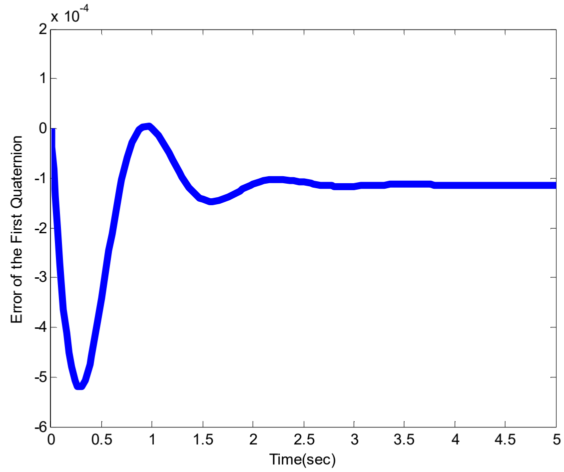

Figure 2. Tracking error of the first quaternion

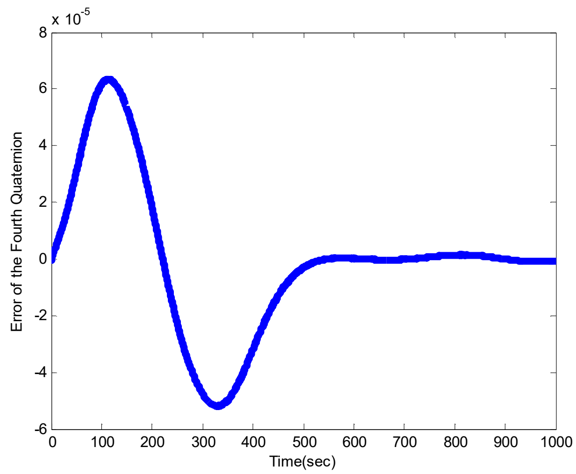

Figure 3. Tracking error of the fourth quaternion

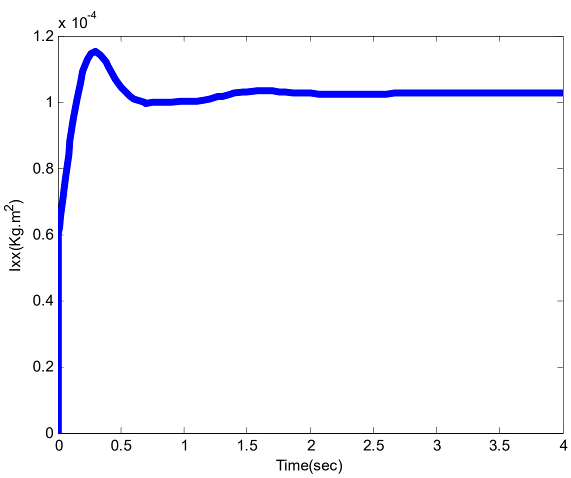

Figure 4. Convergence of I_{xx}

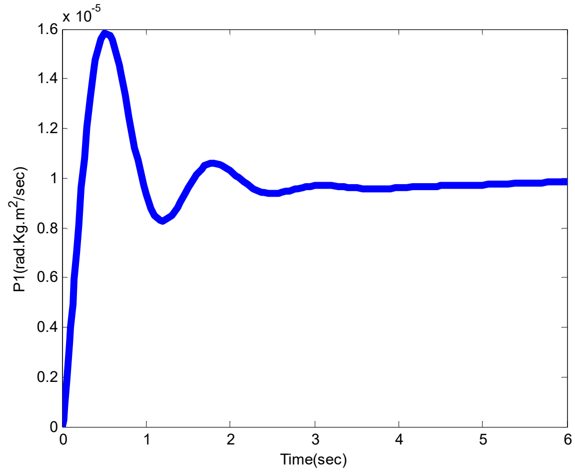

Figure 5. Convergence of P_1

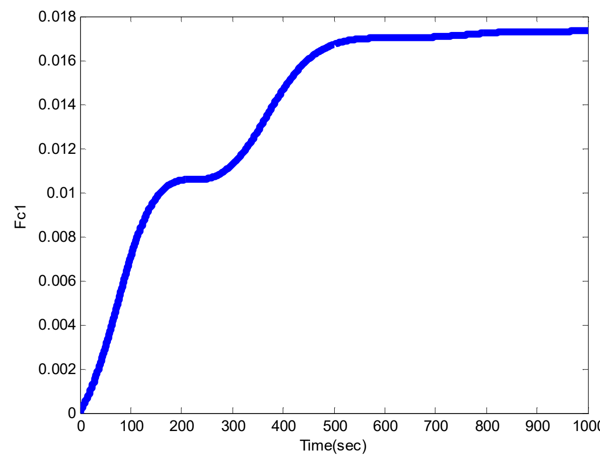

Figure 6. Convergence of F_{C1}

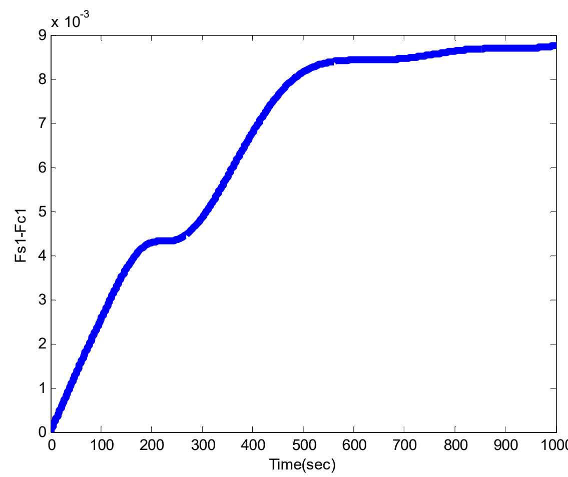

Figure 7. Convergence of $F_{S1} - F_{C1}$

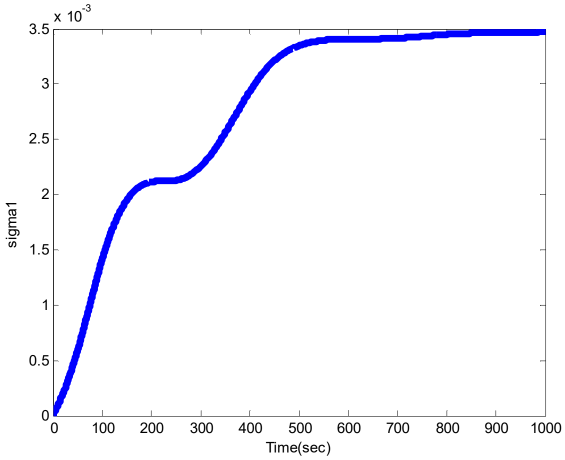

Figure 8. Convergence of σ_1

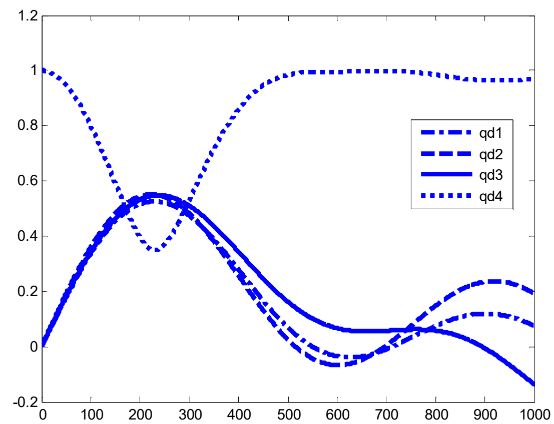

Figure 9. Desired path for four quaternion parameters

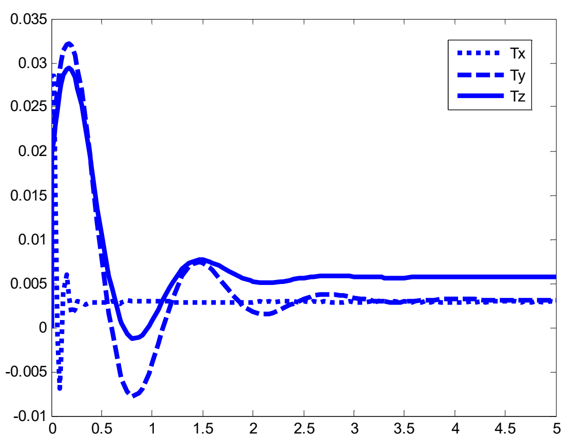

Figure 10. Torque of the reaction wheels that are aligned with x, y, and z-axis

V. CONCLUSION

All of the chosen parameters are converged below one thousand second instead of the parameters that are related to friction. The results show that these parameters change calmly during the run. Although a rich input was chosen with five harmonics in each desired path, the parameters didn't converge to its real value, however, the entire path errors converge to zero instead of the later one. It should be mentioned that the maximum value of the torque is 30 (mN.m). Therefore, none of the actuators will be saturated.

A nonlinear identification is suggested before the implementation, because if the parameters close to real parameters, the control effort will be less.

The next step of this project is designing a nonlinear observer or usage of an adaptive Kalman filter to do noise rejection.

VI. APPRECIATION

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