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Performance evaluation of a fuzzy variable structure satellite attitude controller under sensor data delay

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Abstract: One of the main sources of uncertainties in controlling the attitude of a satellite is the time delays seen in sensor data. Although it is possible to process sensor data to correct the deficiencies caused by delays, it is more suitable to design the controller robust enough to handle uncertainties well. In this study, the attitude of a 3-degrees of freedom satellite model, incorporating uncertainties (both sensor data delay and actuator misplacements), is controlled using a suitably designed fuzzy variable structure controller (FVSC). The performance of the FVSC is evaluated and compared to that of other reference controllers [proportional-derivative (PD), linear-quadratic-Gaussian (LQG), and loop-shaping controllers (LSCs)]. The FVSC performs well in both nondelayed and delayed ($T_d = 0.2$ s and 0.4 s) cases, while the PD and LQG controllers provide good response only for nondelayed cases (i.e. $T_d = 0$ s). A robust LSC also performs well in both cases, but its root mean squared error is high compared to the FVSC in the delayed case.

Key words: Actuator misplacement, fuzzy variable structure control, robust loop shaping controller, satellite attitude control, sensor data delay

1. Introduction

The control of time delay systems is a difficult task, where severe stability problems are encountered. A strict reduction in the control bandwidth is also seen. Using a Smith predictor in the system is a well-known method in alleviating time delays [1]. This method is usually used to show the performance of novel methods in the literature. It generally solves the problem when the model of delay is known well. However, this is rarely the case, where the controllers are implemented using digital techniques, which usually involve variable time delays. The discretization process in the controller is one of the main sources of the time delays encountered in the system. Time delays caused by sensor and actuator systems are other sources, as well as the slow response of the plant.

There are other methods that are more effective solutions when the variable nature of the delays in practical applications is taken into account. One is to use an extrapolation method to predict the nondelayed feedback signal to compensate for the delay [2–6]. In another method, called the digital redesign method, a model of the delay is incorporated into the controller, while discretizing it [7]. Using a disturbance observer to compensate for the delays is another effective method [8–10]. However, designing the controller with a better capability to handle uncertainties is more effective to avoid delays in the system. Additionally, the controller will be more immune against uncertainties other than the ones caused by time delays [11,12].

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As we look at recent literature regarding the use of variable structure control (VSC) and fuzzy control (FC) techniques, they are used separately in order to synthesize a robust controller for the attitude control of various types of satellites and good results are obtained. In [13,14], the authors applied various VSC techniques to satellites using solar sails as attitude control actuators. Jia et al. proposed using VSC in the attitude control of a multibody satellite to attenuate the disturbance caused by the antenna pointing system [15]. Hu et al. also used VSC in the satellite attitude control to prevent vibrations caused by the flexible structure of the satellite [16].

FC is also considered in many studies regarding the attitude control of satellites. The study by Heydari et al. is a recent, good example study, where FC was used alone in the magnetic attitude control of a satellite [17]. Cheng et al. also gave an example of using pure FC in satellite attitude control, where an excellent reference to using it was also presented [18,19]. Guan et al. studied the vibrations caused by flexible structures such as solar panels, and used artificial neural networks along with FC to make the control system adaptive [20]. Nagarajan et al. devised an adaptive predictive fuzzy control approach to the classic satellite attitude control problem [21,22].

There are very few studies that combine FC and VSC, The fuzzy VSC (FVSC) concept was investigated through a very simple satellite model without any delay in the system in [23,24]. Dong et al. proposed a method in which the attitude stabilization of a networked flexible spacecraft during a large angle slew maneuver was achieved by a novel type of adaptive fuzzy sliding mode control (SMC) [25]. The novel method was proposed to solve the problem of attitude control of a satellite with a dynamic model incorporating network-induced delay, and nonlinear and uncertain parameters. Dong et al. also evaluated the effects of time-varying network-induced delays of up to $T_d = 0.2$ s. However, the proposed controller remains too complex for the practical attitude control of a picosatellite. Hence, they then proposed the new technique for a microsatellite, where the network-induced delays are handled by a predictor. Thus, it is hard to see whether the immunity against time delays comes from the SMC or predictor.

The main objective of this study is to design a new robust controller that integrates the FC and VSC techniques, and show its performance under model uncertainties that are mainly time delays in sensor systems and actuator misplacements. In this paper, 3 controllers are designed additionally to compare performances with: one is a classic proportional-derivative (PD)-type controller, the second is a linear quadratic Gaussian (LQG) controller, and the third is a robust loop shaping controller (LSC). The fourth is the FVSC, which is the main objective in the study [26]. The need for an integral term is eliminated through changing the structure of the FC part and adjusting the other controller parameters to more suitable values in the study. The performances of all the controllers are determined under delays of $T_d = 0$ s, $T_d = 0.2$ s, and $T_d = 0.4$ s in the sensor systems to prove the robustness of the controllers. Uncertainties due to actuator misplacement are presented in both the delayed and nondelayed cases. The FVSC is found to handle uncertainties well, especially those caused by delays in the system, with the performance of the LSC being very close to it.

The authors aim to see the effectiveness of the FVSC in controlling the attitude of a picosatellite under heavy sensor delay and compare its performance against a robust controller such as the LSC. The importance of the study resides in the simplicity of the proposed solution. The study is novel in the respect of handling the time delays in the system.

2. Satellite model

The satellite model is a 3-degrees of freedom model, whose mathematical basics can be found in detail in the literature [27–29]. It consists of 2 parts as dynamic equations of motion (DEM) (1a) and kinematic equations of motion (KEM) (Eq. (1b)), which are provided below:

$$DEM\dot{\omega} = I^{-1}(\tau_a - \omega \times (I\omega)), \tag{1a}$$

$$KEM\dot{q} = (1/2)\,\Omega\, q, \tag{1b}$$

where $\Omega = \begin{bmatrix} 0 & \omega_1 & -\omega_2 & -\omega_3 \\ \omega_1 & 0 & \omega_3 & -\omega_2 \\ \omega_2 & -\omega_3 & 0 & \omega_1 \\ \omega_3 & \omega_2 & -\omega_1 & 0 \end{bmatrix}$.

First, the input torque is converted to an angular acceleration by the DEM, which is an implicit expression. The angular velocity can be obtained by integrating the DEM. Next, the angular velocity is input to the KEM to obtain an angular position, which represents the satellite attitude in the quaternion representation. The KEM is also an implicit expression and it must be integrated to obtain the quaternion attitude after its solution using the angular velocity and initial quaternion attitude. In this study, the initial values of the angular velocity and attitude are accepted as 0.

The general view of the MATLAB/Simulink model used in the study is given in Figure 1. Accompanying the satellite model, there are sensor and actuator models. The sensor model is a very simple unity gain block in the nondelayed case. A unit delay block is used to simulate the delay in the sensor system. Two different delay levels, $T_d = 0.2$ s and $T_d = 0.4$ s, are assumed in the delayed case. The sensor system is assumed as proof from errors and noises. Our aim is to see the effects of uncertainties regarding the time delays in the sensor system, alone.

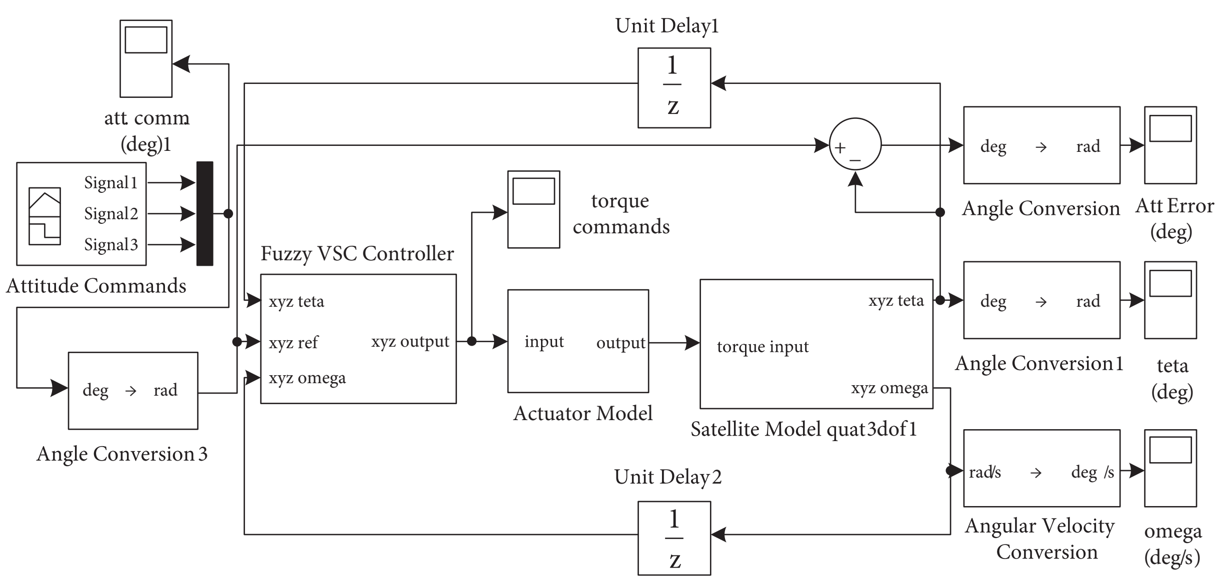

Figure 1. General view of the Simulink model with FVSC.

The actuator model incorporates a means used to model the actuator misplacement, as well as gain and saturation blocks. The actuator misplacement leads to errors in the input torque seen on the satellite body. An input torque in 1 axis generates torques in the other 2 axes as a result. This is accomplished using a cross-coupling coefficient matrix. The torque commands coming from the controller are processed first by a saturation block, which sets the maximum actuator torques to ± 10 mN.m, which is a typical value for a picosatellite. Next, the input torque vector is multiplied by the cross-coupling coefficient matrix to derive the final torques applied to the satellite body model. The cross-coupling matrix is a 3×3 matrix, whose root of sum of squares of the elements of its columns is equal to 1. In the study, from each of the 3 axes, a 2% torque distribution to other 2 axes is assumed. The actuator misplacement adds further uncertainty to the model and it is retained in both the delayed and nondelayed cases. As a result, the actuator model is a unity gain first-order system apart from the saturation and misplacement terms [26].

The moment of inertia (I) of the satellite for each principal axes is 0.01 kg.m^2 and 0 for the other components. The controller seen in Figure 1 is the FVSC. The FVSC uses both angular velocity and position signals as feedback from the sensors. The other controllers use only the angular position signal. Apart from this difference, the simulation environment and attitude commands are the same for the other controller types. Controllers produce a suitable torque command by looking at the given attitude command and feedback from the sensors. These torque commands are then translated to actual torques by the actuator block and applied to the satellite body model.

The attitude commands, whose 300 s-duration patterns are shown in Figure 2, are provided by a signal builder block. The commands are converted to radians and then applied to the reference input of the controller block. They are selected as sharp-edged step functions. Slew rate limiting, which is a common practice in satellite attitude control, is not preferred to present the marginal performances of the controllers.

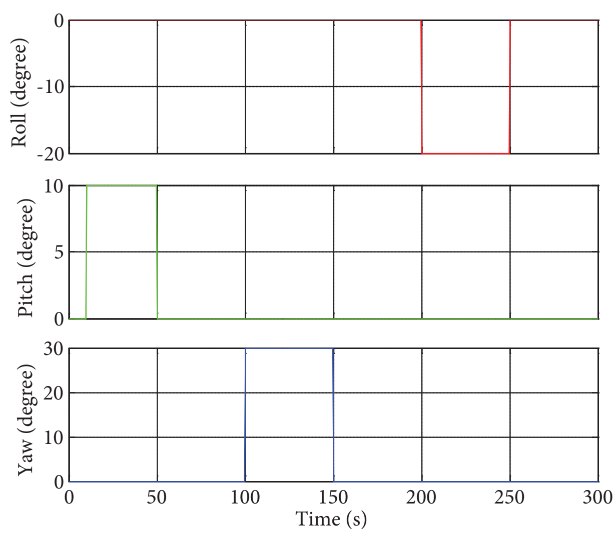

Figure 2. Attitude commands used in the study.

3. Controller design

We mainly design the FVSC. Three other controllers, PD, LQG, and LSC, are used for comparison purposes. The PD controller parameters are selected as $K_P = 1$ and $K_D = 2$ [26]. Detailed information on PD satellite attitude controller design can be found in [30].

The PD, LQG, and LSC use only Euler angles as feedback input, whereas the FVSC uses both the angular position (teta) and velocity (omega) as feedback inputs. The LQG and LSC are designed as a series compensator whose parameters are obtained optimally using the MATLAB control and estimation toolbox. The internal structure of the FVSC is shown in Figure 3. Only one axis is shown for simplicity. All of the parameters and the topology are the same for the other axes. First, a FC is seen in Figure 3. The switching block follows the FC, which switches the output. The switching block is controlled via a suitable switching function, which produces the firing signal from the angular position error and angular velocity signals. The controller is in fact a PD controller, where it is controlled on a sliding line produced by the contribution from the switching block. The sliding line provides robustness to the controller by changing the structure of the controller, hence the name 'variable structure controller'.

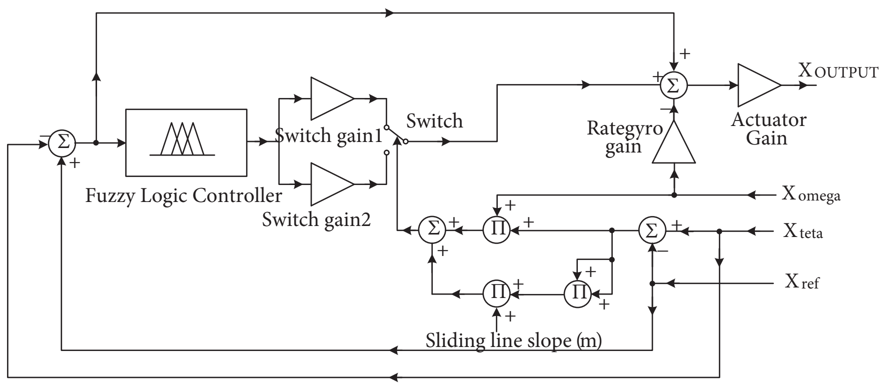

Figure 3. Internal structure of the FVSC. Only one axis is shown, the others are the same.

The design of the FVSC is established according to [23,24,26,31–35]. First, a suitable switching function, S, is selected. The switching function sets the sliding line, which provides robustness in the controller. The switching function used in the FVSC is presented in Eq. (2).

$$S = (\theta - \theta_r).(\omega + m.(\theta - \theta_r)) \tag{2}$$

The switching function output (S) determines the sign of the final output of the FC. The FC output is scaled by switch gain blocks and then switched according to the actual value of the S. FC adds further robustness to the controller [23,24,26]. The parameter 'rate gyro gain' sets a gain factor for the angular velocity sensor. This parameter does not only model the rate gyro sensor, it also provides stability in the system by limiting the angular velocity. This also provides conservation in the control energy, which is vital in satellite attitude control. This term also helps to eliminate a separate integral term, which is mentioned in [26]. We can set the integral term to 0 by selecting a suitable rate gyro gain in the study. The controller is also novel in design because the FC part of the system has a different structure than that in [26]. The parameters of the FVSC are listed in detail in Table 1. Since the parameters in Table 1 can have different units in different applications of the controller, the units can be changed. For example, the unit of the actuator gains can be Nm/V for an analogue actuator, as it is in this application, and can be just a binary numeric value, such as 1 least significant bit digit change per mNm for a digital type of actuator.

Table 1. Parameters used in the FVSC.

Parameter	Value	Parameter	Value
Rate gyro gain	1.48 Vs/rad	Switch gain	±3.6 V/V
Sliding line slope, m	0.1 s^{-1}	Actuator gains	0.01 Nm/V

FC uses the angular position error as input. The input and output membership functions and rule base of the FC are presented in Figures 4 and 5, and Table 2, respectively [23,24,26]. The membership functions are selected as triangles. The input range is ± 0.5 radians, as seen from Figure 4. The output range of the FC is ± 0.1, as seen from Figure 5. The input memberships are negative N, positive P, and 0, while the output memberships are low L, neutral N, and high H. FC is a Mamdani-type controller and uses the centroid method of defuzzification, which is accomplished using Eq. (3).

$$z^* = (\int \mu_{(z)} .zdz)/(\int \mu_{(z)} dz) \quad (3)$$

Here, $z*$ is the defuzzified output; $\mu_{(z)}$ is the aggregated membership function, which is obtained from the fuzzified inputs using the input and output membership functions and rule base; and z is the output variable. Note that the structure of the FC used here is different from the one in [26]. The FC is redesigned to provide extra robustness in this study.

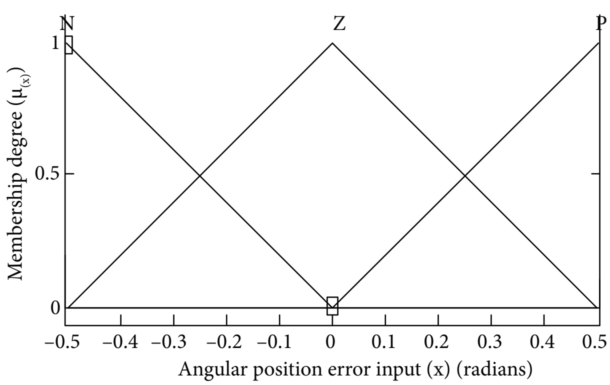

Figure 4. Angular position error input membership function of the FC.

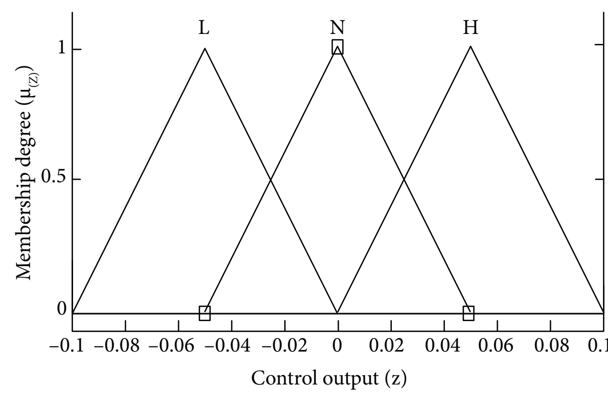

Figure 5. Output membership function of the FC.

Table 2. Rule base of the fuzzy logic controller.

1	If error is N then output is H
2	If error is Z then output is N
3	If error is P then output is L

4. Results and discussion

The performance of all of the controllers is evaluated through error graphs and a comparison is made using root mean squared (RMS) errors in each of the 3 axes. The controllers are tested under no delay, and T_d = 0.2 s and T_d = 0.4 s sensor delay cases, to prove the robustness and stability of each controller. Uncertainty regarding the 2% actuator misplacement is presented in all cases. The angular position error graphs of each controller are shown in Figures 6–9 for the no-delay case. They are presented in Figures 10–13 for the T_d = 0.4 s sensor data delay. In Figures 6–13, the errors of 3 axes (roll-pitch-yaw) are presented in separate axis systems, time-synchronized to each other. Only in Figures 10 and 11 is the last second zoomed in on to show the oscillations effectively. In this case, this part is presented in a separate axis, time-synchronized to the other axes, but having different y-axis ranges to zoom in on the amplitudes. No graph is presented for the intermediate delay level, Td = 0.2 s. Only the RMS error figures are presented for this case.

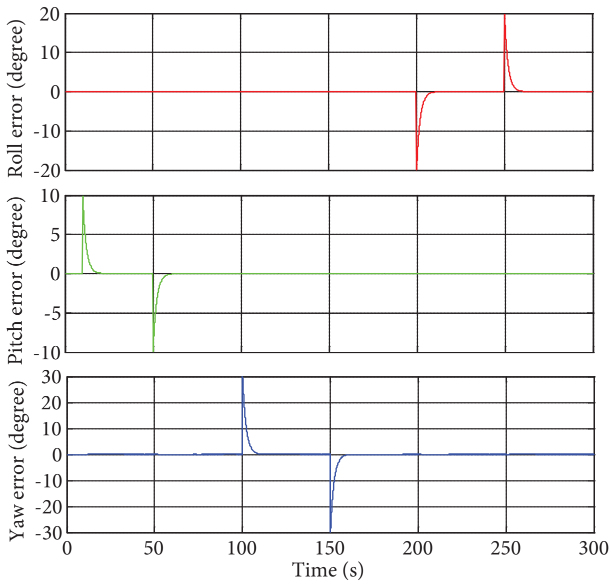

Figure 6. Angular position error graph of the PD controller ($T_d = 0$ s).

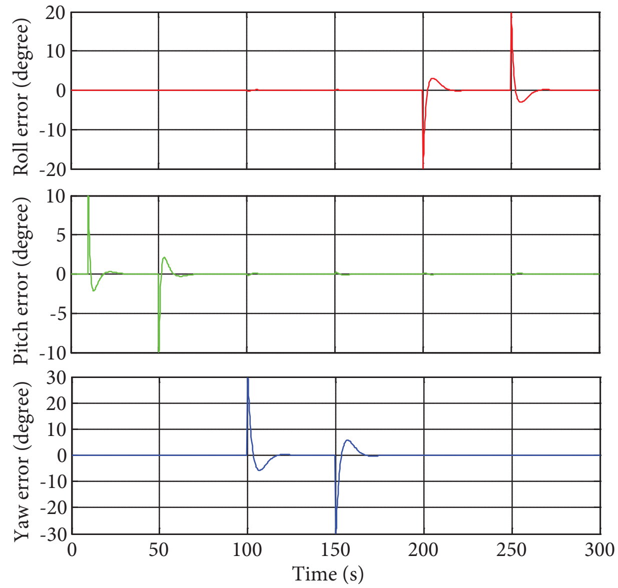

Figure 7. Angular position error graph of the LQG controller ($T_d = 0$ s).

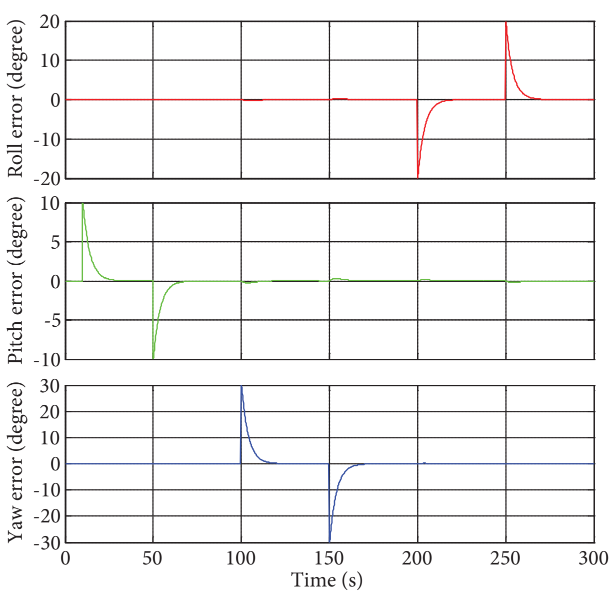

Figure 8. Angular position error graph of the LSC ($T_d = 0$ s).

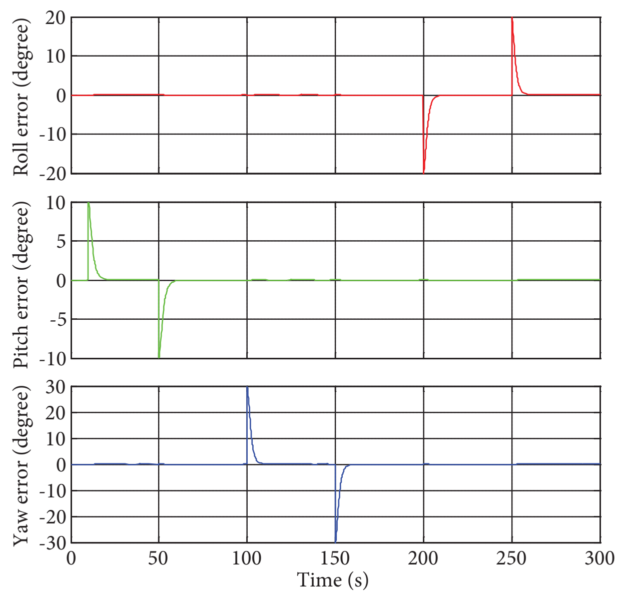

Figure 9. Angular position error graph of the FVSC ($T_d = 0$ s).

It is clearly seen from Figure 6 that the PD controller gives the best result for the no- delay case, with only a transient error in the output. These transients can be omitted, since they can easily be suppressed using a suitable slew rate limited attitude command, which is a common practice in satellite attitude control. On the other hand, the response of the LQG controller (Figure 7) additionally contains small amplitude overshoots. The LSC (Figure 8) also gives smooth performance except, settling that the time is the longest among the others. The FVSC produces a more acceptable result (Figure 9) than the LQG controller (Figure 7), resembling the PD controller. The settling time of the FVSC is also low compared to the others.

As seen from Figures 10–13, which show the error graphs of the controllers for the $T_d = 0.4$ s sensor delay case, both the PD and LQG controller become unstable and give way to large amplitude oscillations. The amplitude of the oscillations reaches $\pm 200°$ at maximum and they are more easily seen in the zoomed last second of the axes (rightmost axes in Figures 10 and 11, respectively). The PD controller becomes unstable at the beginning (Figure 10), while the LQG controller also becomes unstable in the middle (Figure 11). This shows that the LQG controller is in its critical limits. There must be a large impact, such as the 30° error in the yaw axis, to make it unstable. The LSC (Figure 12) produces an acceptable response in terms of the error, but the settling time is long compared to that of the FVSC (Figure 13). The FVSC continues its stable operation. There are small amplitude oscillations in the transient regions, but they are damped quickly (Figure 13). Due to these oscillations, the settling time is included in the FVSC and becomes comparable to the settling time of the LSC. As will be seen later from the comparison of the RMS errors, the FVSC performs better than the LSC under sensor delay, despite the error graphs of the LSC being much smoother. This is attributed to the high settling speed of the FVSC.

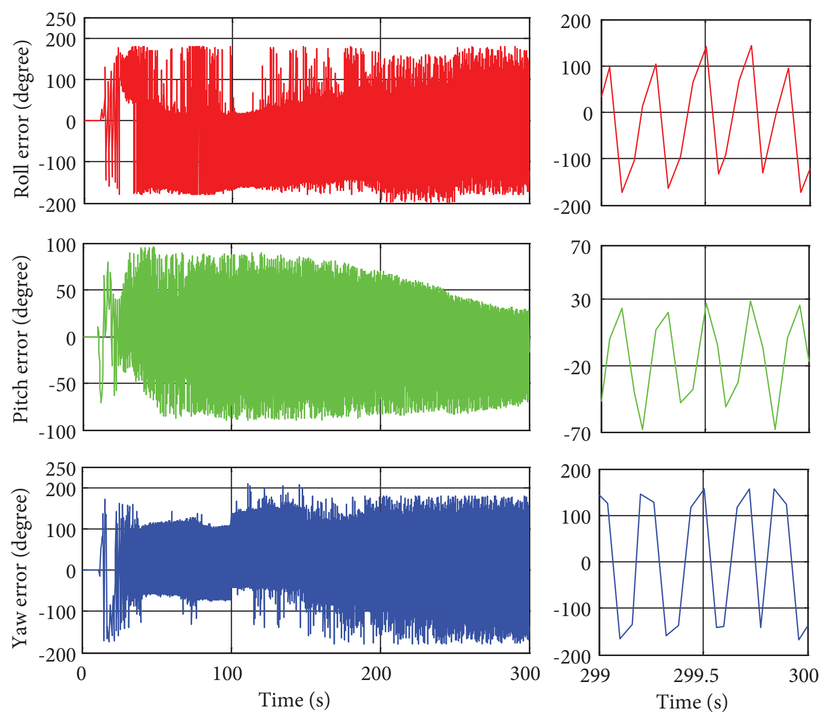

Figure 10. Angular position error graph of the PD controller ($T_d = 0.4$ s).

When the RMS errors of the controllers for both the delayed and nondelayed conditions are compared, the results are seen more clearly. The RMS errors for the 3 axes of the controllers for 3 different cases are presented in Table 3. Each number in parentheses refers to the RMS error of 1 of the axis in the roll-pitch-yaw order in degrees. It is clear from Table 3 that the PD controller performs well in the nondelayed case. However, the PD controller becomes unstable with delay in sensor systems and the RMS error is unacceptably large in this case. The LQG controller also performs well in the nondelayed case, but when a delay is introduced, the error also grows large. However, it is not as large as that of the PD controller, since the LQG controller is in its critical limits. The RMS error of the LSC is the second largest of all of the controllers for the nondelayed case, with the largest one being the RMS error of the FVSC. The LSC performs well in the delayed case, where even its error is reduced in the delayed cases. While the FVSC performs badly in the nondelayed case compared to the others, it performs very well in the delayed case. The FVSC performs better in delayed cases. It is, in fact, the best performance of all for the delayed cases.

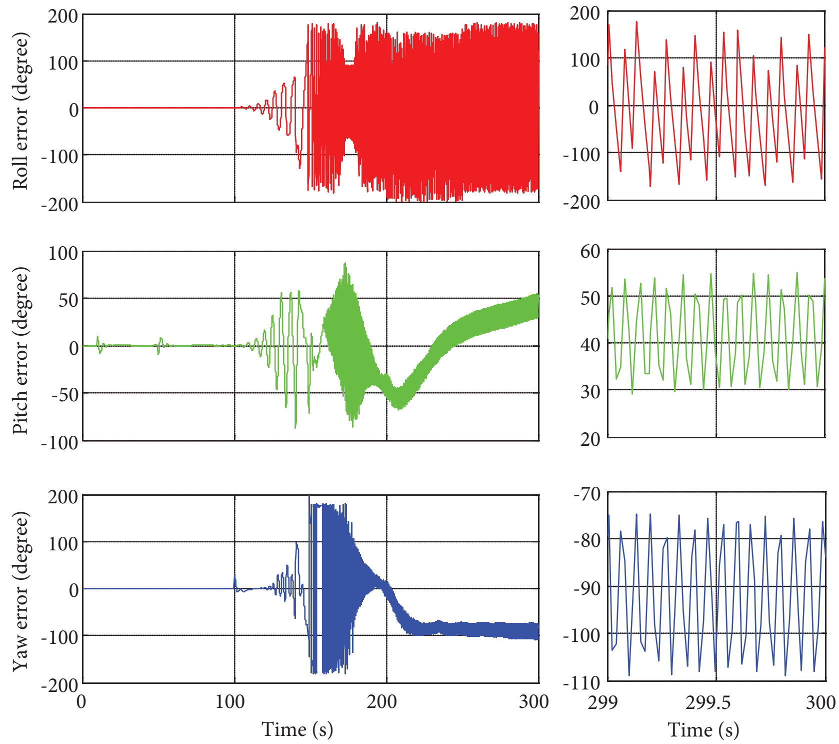

Figure 11. Angular position error graph of the LQG controller ($T_d = 0.4$ s).

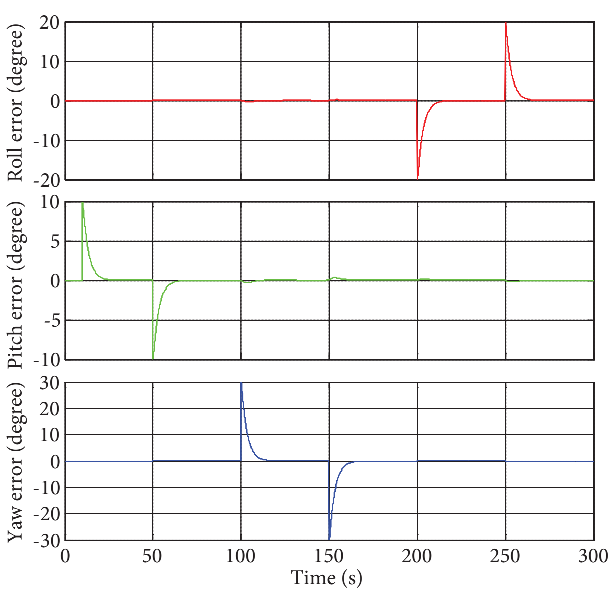

Figure 12. Angular position error graph of the LSC ($T_d = 0.4$ s).

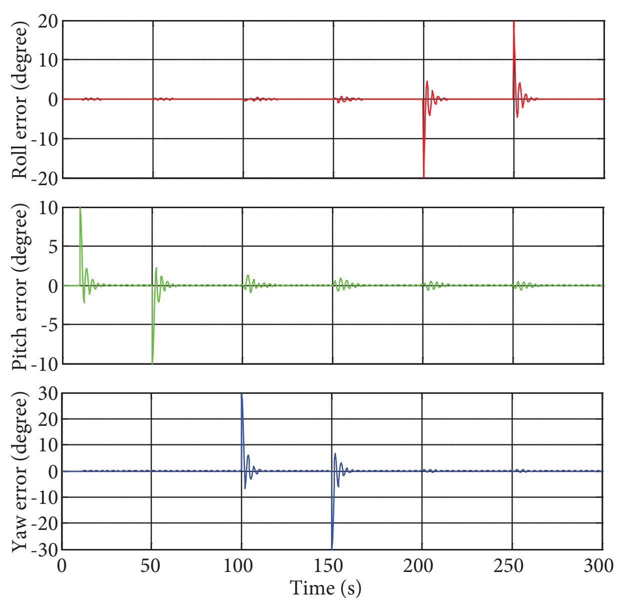

Figure 13. Angular position error graph of the FVSC ($T_d = 0.4$ s).

Table 3. RMS errors of the controllers for delayed and nondelayed cases.

Controller type	RMS error ($T_d = 0$ s) (degree)	RMS error ($T_d = 0.2$ s) (degree)	RMS error ($T_d = 0.4$ s) (degree)
PD	(2.1071 1.2998 4.1180)	(104.6569 38.8736 133.0711)	(113.8793 47.6426 114.3441)
LQG	(3.2641 1.4921 5.3327)	(2.5196 1.1982 4.2820)	(91.0732 31.8291 87.4262)
LSC	(3.6564 1.8247 5.6874)	(3.3659 1.6848 5.0728)	(3.2061 1.6058 4.8353)
FVSC	(4.6389 2.9130 8.9814)	(1.7885 0.9015 2.6732)	(1.8821 0.9539 2.8197)

5. Conclusion

In this study, 4 controllers are designed for the attitude control of a picosatellite: the 1st is a classic PD type controller, the 2nd is a LQG controller, the 3rd is a LSC, and the 4th is the FVSC. The performances of all 3 controllers are determined under 2 cases: no delay in sensor systems ($T_d = 0$ s) and delay in sensor systems ($T_d = 0.2$ s and $T_d = 0.4$ s).

The results are evaluated and a comparison between these 4 controllers is made according to the RMS error. The PD controller gives good results in controlling the satellite model with no time delay. The LQG controller has little overshoot in the response for the same case. The LSC also performs well in this case, despite its settling time being a little longer compared to the others. The FVSC also gives comparable results without a delay in the system. The FVSC also has the lowest settling time for this case. Where the delayed cases are concerned, both the PD and LQG controllers perform badly. The PD and LQG controllers become unstable with large amplitude oscillations in the attitude, which is clearly unacceptable for an application like satellite attitude control. On the other hand, both the LS and FVS controllers remain stable with a time delay in the sensor systems. The RMS error of the LS and FVS controllers decreases slightly. The lowest RMS error in the delayed case is seen in the FVSC. According to the RMS errors, the FVSC handles error more properly and its robustness is very high considering that the time delay introduced is relatively large. Moreover, the settling time of the FVSC is low compared to the other controllers. As a result, the FVSC can be preferred over the other controllers since the latest technological improvements enable a satellite to carry a more sophisticated attitude control computer. However, since the LSC is a more simplistic solution to the satellite attitude control problem and the RMS error performance is very close to that of the FVSC, it can also be a good candidate. A comparison can be carried out over on the control energy performances of these controllers in a future study, since the FVSC promises a lot in the conservation of fuel consumption, which is very important in the attitude control application of a satellite.

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Nomenclature

ω	Angular velocity vector in the body axes, $[\omega_1\ \omega_2 \omega_3]^T$ (rad/s)
θ	Actual attitude Euler angle vector in the body axes, $[\theta_1 \theta_2 \theta_3]^T$ (rad)
θ_r	Reference attitude Euler angle vector in the body axes, $[\theta_{r1} \theta_{r2} \theta_{r3}]^T$ (rad)
$\theta_{e(RMS)}$	Root mean square (RMS) attitude angle error (degree)
I	Moment of inertia matrix (kg.m^2)
τ_a	Actuator torque vector, $[\tau_{a1} \tau_{a2} \tau_{a3}]^T$ (N.m)
q	Quaternion attitude vector, $[q_0\ q_1\ q_2\ q_3]^T$, where q_0 is the scalar component
Ω	Coefficient matrix
m	Sliding line slope coefficient
S	Switching function output
T_d	Sensor data time delay (second)

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