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Development of a Hardware-in-the-loop Simulator for Spacecraft Attitude Control Using Thrusters

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Abstract

In this study, a Hardware-In-the-Loop (HIL) simulator using thrusters is developed to validate the spacecraft attitude system. To control the attitude of the simulator, eight cold gas thrusters are aligned with roll, pitch and yaw axis. Also linear actuators are applied to the HIL simulator for automatic mass balancing to compensate the center of mass offset from the center of rotation. The HIL simulator consists of an embedded computer (Onboard PC) for simulator system control, a wireless adapter for wireless network, a rate gyro sensor to measure 3-axis attitude of the simulator, an inclinometer to measure horizontal attitude, and a battery set to supply power for the simulator independently. For the performance test of the HIL simulator, a bang-bang controller and Pulse-Width Pulse-Frequency (PWPF) modulator are evaluated successfully. The maneuver of 68 deg. in yaw axis is tested for the comparison of the both controllers. The settling time of the bang-bang controller is faster than that of the PWPF modulator by six seconds in the experiment. The required fuel of the PWPF modulator is used as much as 51% of bang-bang controller in the experiment. Overall, the HIL simulator is appropriately developed to validate the control algorithms using thrusters.

Keywords: hardware-in-the-loop (HIL) simulator, spacecraft attitude control, thrusters, bang-bang controller, PWPF modulator

1. Introduction

With the development of the spacecraft technology, the ability which duplicate real space environment is very important. To test the attitude control algorithm for spacecraft, the torque-free environment is required. Ground-based experiment for spacecraft attitude control using hardware simulators have been developed and researched during last decade (Schwartz et al. 2003). Hardware-in-the-loop (HIL) simulator has advantages for validation of the attitude control algorithm. Air-bearings have been used for satellite attitude determination and control hardware verification. They do allow for the manipulation of hardware simulator in a minimal-torque environment (Schwartz et al. 2003). Many types of the air-bearings are developed in the past. Among these types, the spherical air-bearing is mostly used to represent the space environment. The earliest system of the spacecraft simulator is a three axis spherical air-bearing and it was developed in 1959 at the U.S. Army Ballistic Missile Agency. Aerospace Robotics Laboratory (ARL) in the Stanford University used air-bearing

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of planar system to investigate the field of in-orbit rendezvous. Moreover, the Stanford University used the spherical air-bearing system in 1975. In 1995, the Three Axis Attitude Dynamics and Control Simulator was developed to demonstrate the dynamics and control of a twin-mirror bifocal relay satellite in Naval Postgraduate School. The School of Aerospace Engineering at Georgia Institute of Technology also developed the first generation testbed in 2001. Moreover, the second generation testbed is developed to investigate the non-linear control (Schwartz et al. 2003).

The first generation of the ACL (Astrodynamics and Control Laboratory) simulator at Yonsei University is designed and developed by the Astrodynamics and control laboratory in 2007 (Kim et al. 2008). The first generation of the ACL simulator is developed for HIL simulator of three-axis attitude control of micro-satellite with the mission in the low Earth orbit and educational instruments for the students. The purpose of the development is the validation of the attitude control algorithm using momentum wheels. Also, Hardware-in-the-Loop simulation technique is used for developing and test real-time embedded systems. The customized three momentum wheels for the HIL simulator are developed and tested. Also, PID controller is implemented to the simulator for verification of the control algorithm (Kim 2008).

In this paper, the second generation of the ACL simulator is designed and developed to extend the ability for the various types of control schemes. The second generation of the ACL simulator newly consists of the thruster system, and linear actuator for the auto mass balancing. This paper also presents the implementation of the control algorithm using thrusters for hardware simulator. Development of the thruster system is focused to perform experimental study of the spacecraft attitude controls. The eight thrusters are aligned along roll, pitch and yaw axis. There are two major approaches for thruster control. One is Bang-bang controller and the other is Pulse modulator. Bang-bang controller is simple in formulation, but it required excessive thruster action. In general, pulse modulators produce a pulse command sequence to the thruster valves by pulse width and pulse frequency (Song & Agrawal 1999). In this paper, the results of implementation using thruster control are compared for the two control algorithms. Accurate balancing of the platform is also necessary to duplicate the space environment as torque-free. Mass balancing system can provide the coincidence between the center of gravity and the center of rotation of the hardware simulator (Kim et al. 2001). Hence, two linear actuators are newly added to the HIL simulator.

2. Overview of the ACL Simulator

The second generation of the ACL simulator is designed by 3D CAD program, Solidworks (Solidworks Corporation 2007). The ACL simulator consists of many hardware parts to implement the attitude control algorithm. In the view of the structure, the ACL simulator has three platforms. The upper and lower platforms are newly designed to the first generation of the ACL simulator. The detailed descriptions of the simulator can be found in the thesis (Koh 2009). The main sensor for attitude angular rate in the the ACL simulator is AHRS400 rate gyro sensor. The coordinates in the AHRS400 are used to represent the body frame of the ACL simulator. Roll and Pitch axes are aligned with the main platform and yaw axis is perpendicular. Actuators to control the attitude of the ACL simulator are aligned to the coordinates. However, momentum wheel assemblies are distributed in equal parts for mass balancing. Because they are not aligned with pitch axis, the transformation axes is used for attitude control (Kim 2008). As compared with momentum wheel assemblies, thruster modules are aligned with all three axes because they are organized according to the symmetric distribution. The linear actuators are also aligned with roll and pitch axes. Because the mechanical structure of the air-bearing system, the center of rotation and the center of gravity are not matched automatically like the space environment. To solve this problem, counterweights are

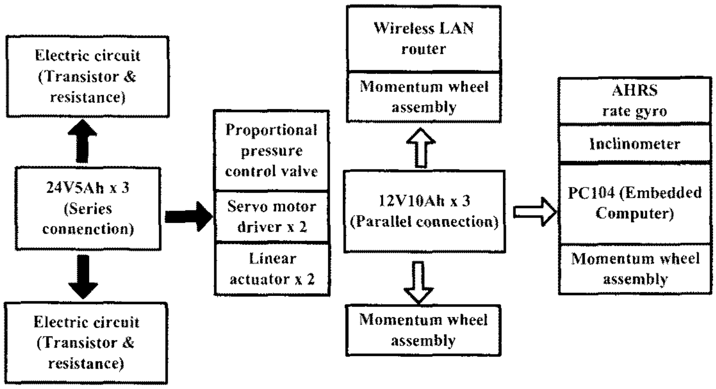


Figure 1. Power diagram of the ACL simulator.

Table 1. Power estimation.

	Input Voltage (v)	Input current (A)	Power Consumption (W)
PC104 module (1)	5	2.99	14.95
Momentum wheel assembly (3)	12	4(MAX)	48
Rate gyro sensor (1)	9~30	0.3	2.7~9
MTi sensor (1)	5	0.2	1
Inclinometer (1)	10~30	0.2	2~6
Wireless network router (1)	7	1.5	10.5
Solenoid valve (8)	24	0.45	11
Pressure control valve (1)	24	0.04	1

used to move the center of gravity in the first generation of the ACL simulator. From the viewpoint of the accuracy, the manual balancing by using the counterweights has the limitation and long time is required for mass-balancing.

As primary actuator, the ACL simulator includes the momentum wheel assembly. It consists of three flywheels, brushless DC motor and motor controller (Kim et al. 2008). Also, thruster reaction control system as additional actuator is designed to extend for validation of the control algorithm. Thruster system consists of solenoid valve, nozzle, gas tank and electric circuit to control On/Off system. Thruster modules in the the ACL simulator are distributed in pairs. In order to implement the control algorithm for three axes, minimum six thruster modules are required. The ACL simulator can rotate to the roll and pitch axis until 20 deg. because of the mechanical structure of air-bearing system. The ACL simulator can rotate 360 deg. to the yaw axis. So the two additional thruster modules are distributed to the yaw axis for extending the level of operation. For sensor of the ACL simulator, Attitude Heading Reference System (AHRS) is used in the first generation of the ACL simulator. The inclinometer is newly used to detect the degree of roll and pitch axes. The AHRS400 sensor which can measure +/- 180 deg. is used for rate gyro sensor. It displays the static accuracy range as +/- 0.75 deg. and the resolution as 0.1 deg. The inclinometer has the ability to measure +/- 30 deg. It displays the static accuracy as 0.3 deg. and the resolution as 0.001 deg.

The ACL simulator consists of the on-board power system. If the ACL simulator operates all

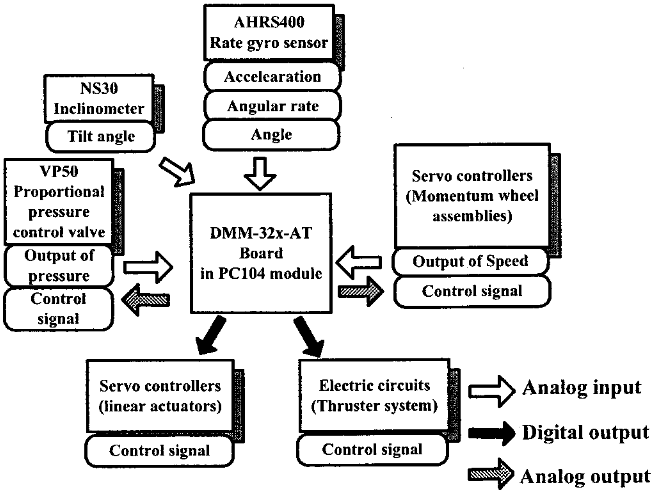


Figure 2. Signal flow of the ACL simulator.

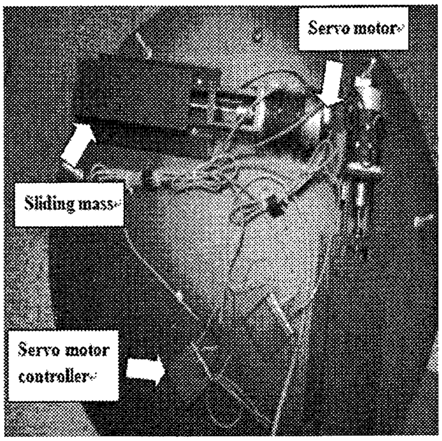


Figure 3. Exterior shape of the linear actuators for auto mass balancing.

modules which are required power supply during one hour, the total power consumption of the ACL simulator is about 275W. Table 1 shows the power estimation for the second generation of the ACL simulator. In general, the micro-satellites in low-earth require the power supply during eclipse. For applying the condition to the HIL simulator, the ACL simulator is designed to operate with the full performance only using battery itself for one hour. The power system can be divided two types. The series and parallel connection of the battery set are applied to the second generation of the ACL

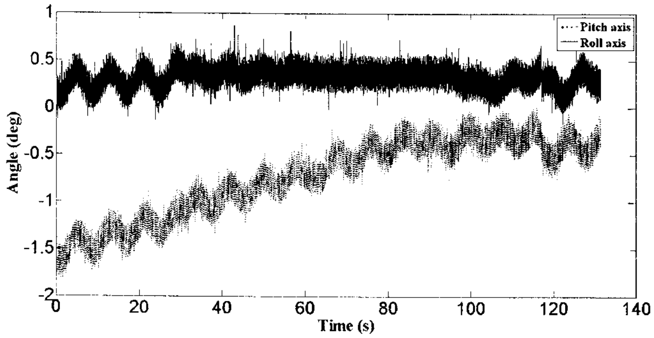


Figure 4. Result of auto mass balancing by using the linear actuator.

Table 2. Comparison between the linear actuator and counterweight.

	Linear actuator	Counterweight
Mass	369.46g (sliding mass)	300∼1200g
The pitch of the lead screw	0.1 inch per motor revolution	N/A
Servo motor resolution	2000 points per revolution	N/A

simulator. All the battery sets are connected with different devices. Mainly, the battery set of series connection are the power source of the thruster system and linear actuators. The parallel connections are connected for momentum wheel assemblies. The Figure 1 displays the power diagram of the ACL simulator. The sensors for attitude control measures the attitude variation described in analog or digital signal. These signals can be processed to operate the HIL simulator according to the control algorithm in the embedded computer. Moreover, each signal has the information to operate the devices. The Figure 2 represents the entire signal flow of the ACL simulator.

3. Auto Mass Balancing

The air-bearing system in the ACL simulator is used to duplicate the space environment. However, the mechanical structure of the air-bearing cause the separation of the Center of Gravity (CG) and Center of Rotation (CR). To solve this problem, the primary solution is suggested by using counterweight (Kim 2008). The manual balancing by using counterweight has the limitation of the accuracy. Hence, the linear actuator system newly designed. The two of linear actuators are attached to the ACL simulator and each linear actuator is aligned with roll and pitch axes. The linear actuator consists of the sliding mass, servo motor, servo motor driver (http://www.oesincorp.com). The Figure 3 shows the exterior shape of the linear actuator in the ACL simulator. To control the servo motor, the pulse signal is generated from the PC104. The step pulse frequency required to operate the linear actuator is 0 to 250 kHz. To prevent the overload of the CPU in the PC104, the 200Hz is used as pulse frequency. Compared with the counterweight for manual balancing, the sliding mass in the linear actuator is lighter. Table 2 shows the comparison between the linear actuator and counterweight.

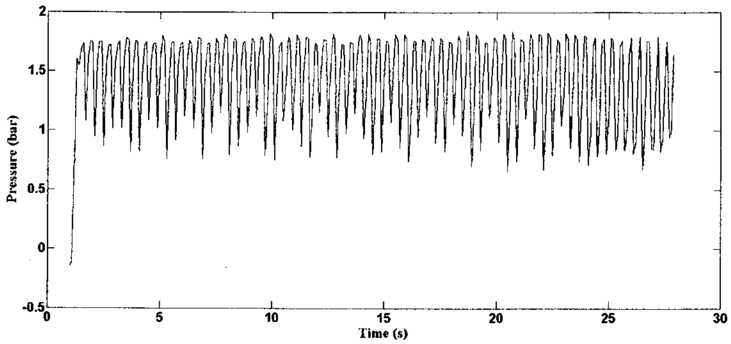


Figure 5. Performance of the proportional pressure control valve.

The above-mentioned methods for balancing the mass have their respective merits. All the ways for the mass balancing of the ACL simulator are applied : Manual balancing by using counterweights and automatic balancing by using linear actuators. In the experiment, the balance of the ACL simulator is adjusted broadly by counter-weights. The manual balancing let the angle of roll and pitch axes reach about 0.5 deg. and –1.5 deg., respectively. After using the manual balancing, the linear actuators are operated to adjust the roll and pitch angles. The Figure 4 represents the result of auto mass balancing by using the linear actuators. In this result, the maximum range to be adjusted is almost 1 deg. Also, this result shows the variation of the roll and pitch angles. The roll angle is maintained by 0.4 deg. and the pitch angle is reached to the –0.5 deg. In the process, it takes 130 sec. The result shows that the center of gravity is nearby adjusted to the center of rotation.

4. Thruster Reaction Control System

The second generation of the ACL simulator has a pressurized gas thruster system as well as a momentum wheel assembly as an actuator. The force acting on the body is then generated when the gas is let out of nozzles. The thruster reaction control system consists of eight solenoid valves and nozzles, one gas storage tank, electric circuit for on/off signal, manual regulator and proportional pressure control valve. Two pairs of thrusters are arranged to the roll and pitch axes. The remaining four thrusters are distributed to the Yaw axis. To generate the thrust force, the nitrogen gas as Cold Gas System (CGS) is used. Moreover, the use of nitrogen gas can reduced the size of nozzles and valves (Abrahmsson 2004). The force generated by thruster is proportional to the pressure of the gas. So it is important to adjust the pressure and maintain the pressure of the gas continuously. During the operation, the manual regulator has the role to control the pressure primarily. It can make the pressure of gas down to 5 $\mathrm{kgf/cm^2}$. The proportional pressure control valve, VP50 is also added to the manual regulator. It has the role to down and maintain the pressure range while two more solenoid valves operates at same time. For check the performance of the proportional pressure control valve, the various input signals are tested. The proportional pressure control valve can make the exact output command according to input signal supplied by embedded computer when the thruster modules are actuated. The Figure 5 displays the results of the performance of proportional pressure control valve with 2 bar as input. The Figure 5 shows that the pressure of gas is uniform per single pulse. The various other levels of pressure can be applied for the attitude

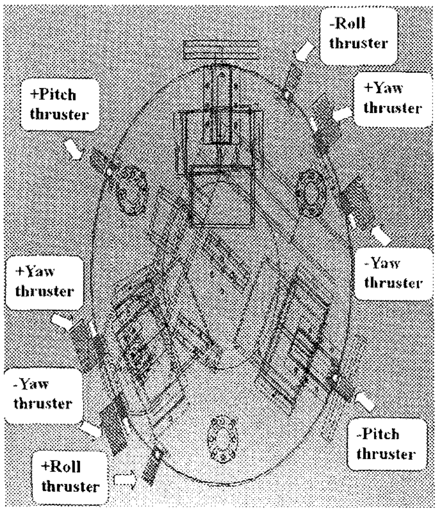


Figure 6. Location of the thruster module.

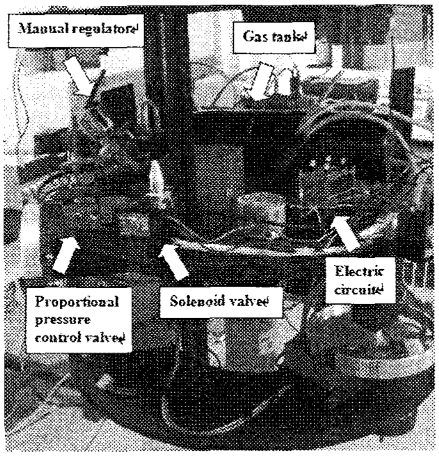


Figure 7. Organization of the thruster system.

control. By using this device, the pressure can be exactly maintained for all nozzles of the thruster module. To keep the thrust magnitude equal for all the thruster modules, the lengths of hose from the proportional pressure control valve are same. Since thruster control system uses only On/Off mode, On/Off control device should be designed with solenoid valve. In order to satisfy this condition, the transistors (TIP41C) and resistances are used to make the electric circuit to control the solenoid valve. The Figure 6 and Figure 7 show the location and organization of the thruster system. The figure 8 represents the operation diagram of the thruster system in the ACL simulator.

5. Control Law for Thrusters

Two types of control algorithms for thruster system are used as actuator in this paper. The first one is bang-bang control and the other is pulse modulator. In general, pulse modulators are commonly used because of their advantages of reduced propellant consumption and near-linear duty cycle. Pulse modulators include pseudo-rate modulator, integral-pulse frequency modulator, and pulse-width and pulse-frequency (PWPF) modulator. The PWPF modulator has the advantages such as near-linear operation, high accuracy and adjustable pulse width and pulse frequency (Anthony & Wie 1989). Bang-bang controller and PWPF modulator are implemented for attitude control of the second generation of the ACL simulator. The Figure 9 shows the ACL simulator which is integrated by all parts. The thruster control system provides the fixed torque. So, the control variable in the thruster system is only the direction of thrust. The bang-bang controller is defined by Eqs. (1,2) (McClelland 1994). U in the Eq. (1) means the magnitude of the thruster on-signal and $u(t)$ is the output signal of the bang-bang controller. The Eq. (2) represents the reference signal, $r(t)$. It means the difference between the desired angle and the combination of gained velocity and position error. The proportional gain is multiplied to the attitude angle $\theta(t)$ and the derivative gain is multiplied to

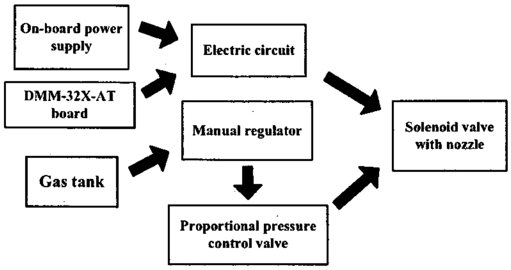


Figure 8. Operation diagram of the thruster system.

the attitude angular rate $\dot{\theta}(t)$. In the Eqs. (1,2), α means the deadzone.

$$u(t) = \begin{Bmatrix} U \cdot \mathrm{sgn}(e(t)) & \text{if} & |r(t)| \geq \alpha \\ 0 & \text{if} & |r(t)| \langle \alpha \end{Bmatrix} \quad (1)$$

$$r(t) = \theta_{desired} - P_{gain} \cdot \theta(t) - D_{gain} \cdot \dot{\theta}(t) \quad (2)$$

In the experiment, the bang-bang controller is applied to the ACL simulator. The pulse width of single thruster is 0.4 sec in the experiment for bang-bang controller. The Figure 10 and 11 show the results of the test by implementation of bang-bang controller. The two types of output pressure are applied to the test for the comparison. The first one is set as 1 bar of output pressure and 2 bar of output pressure is applied to the other. The test performs the maneuver of 68 deg. in yaw axis. According to the pressure of the thruster, the results show the different settling time. In this experiment, the settling time of the two output pressures is about 53 sec and 27 sec for Yaw axis, respectively. In the bang-bang controller, the total magnitude of thrust is proportional to output pressure. Hence, the settling time should be inversely proportional in the test. Both test results shows that 4 deg. of yaw angle error is maintained still. Similarly, yaw angular rate oscillates within the range of 2 deg/sec. These error is caused by the initial state of the ACL simulator. Because CG and CR of the ACL simulator is not matched exactly. Figure 12 shows the direction and firing time of the thrust during the operation. The result shows that the direction is only changed during the operation. This means that the control torque in the sampling time is same. Hence, the thrust firing of the bang-bang controller is always maintained and the total firing time of the settling time is 27 sec.

The Pulse-width pulse frequency (PWPF) modulator provides a variable average thrust using a simple On/Off thruster. Therefore an approximation to proportional control is achieved. The PWPF modulator can be expressed by Eq. (3) (Krovel 2005). In the Eq. (3), f(t) is the output signal of the transfer function in the PWPF modulator and the laplace transform is applied. The PWPF modulator includes the transfer function for filter, relay with dead-zone and Schmitt trigger. Also, $r(t)$ and $u(t)$ represent the reference signal and output signal from the PWPF modulator. Filter gain K_m and filter time constant T_m are the parameters of the transfer function in the PWPF modulator. The Schmitt trigger is an on-off relay with a deadzone and hysteresis. Hence the output signal can be modulated by feedback loop of the transfer function and Schmitt trigger. The PWPF modulator only determines the characteristics of the pulse for output signal according to the input signal. By implementation of

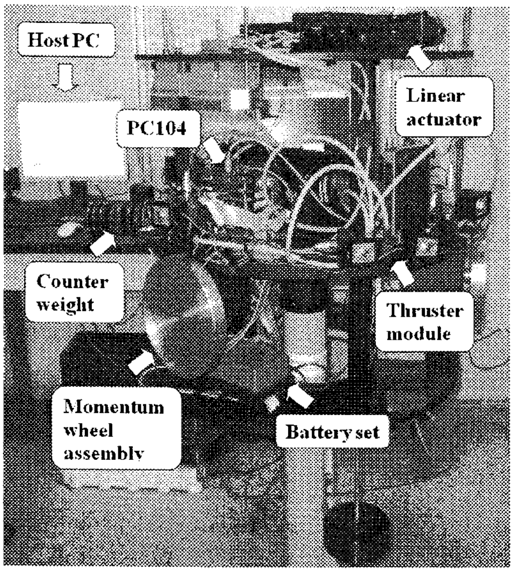
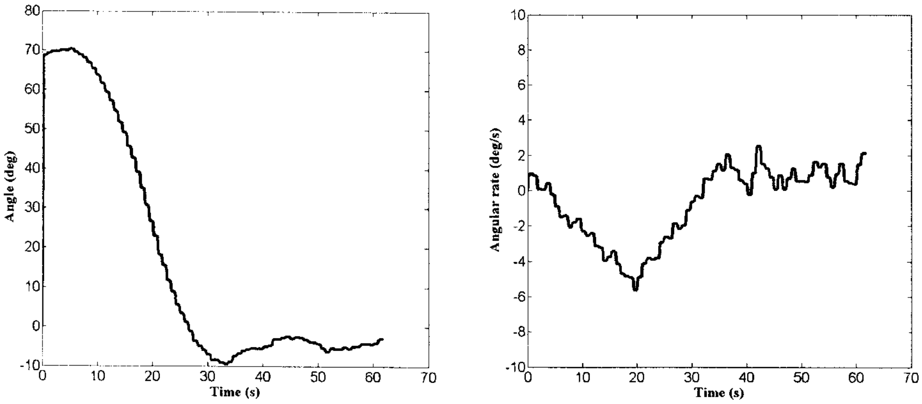


Figure 9. Full veiw of the ACL simulator.



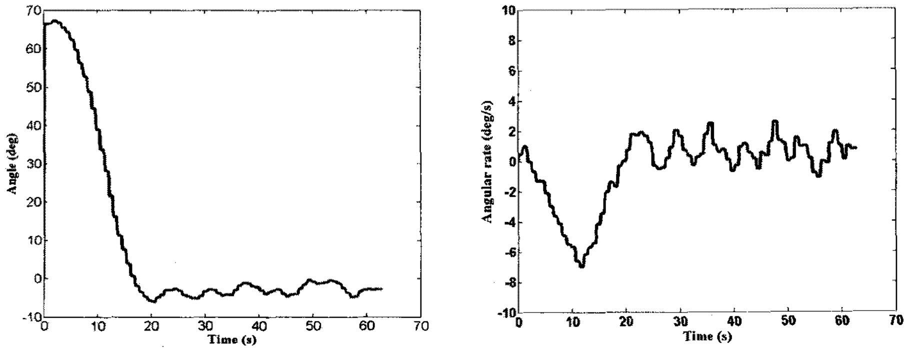
(a) History of yaw angle. (b) History of yaw angular rate.

Figure 10. Experimental results of the bang-bang controller for thruster with 1 bar pressure.

the the PWPF modulator, the variable pulse signal can be used as input signal to the thrust control system.

$$f(s) = e(s)\frac{K_m}{(T_m s + 1)} + \frac{T_m f(0)}{T_m s + 1} \tag{3}$$

$$e(s) = r(s) - u(s) \tag{4}$$



(a) History of yaw angle. (b) History of yaw angular rate.

Figure 11. Experimental results of the bang-bang controller for thruster with 2 bar pressure.

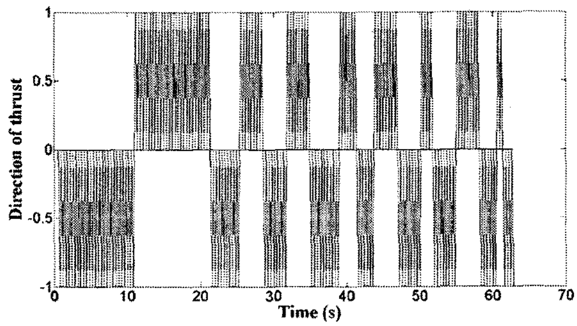


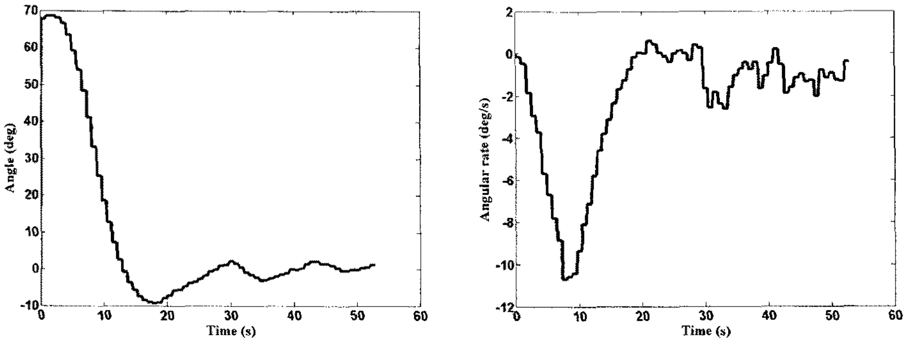
Figure 12. Thrust firing of the bang-bang controller using the thruster with 2 bar pressure.

Table 3. Comparison of the test results.

	Bang-bang controller	PWPF modulator
Settling time (sec)	27	33
Firing time (sec)	27	13.9

The Figure 13 shows the result of the PWPF modulator. Similar to the result of the bang-bang controller, the Figure 13 shows the oscillation continuously. The range of yaw angle error is about 3 deg. and the yaw angular rate is about 2 deg/sec. Likewise, the reason for this error is incoincidence of the CG and CR. The settling time in the Figure 13 is about 33 sec. Moreover, the Figure 14 represents the thrust firing of PWPF modulator. By using PWPF modulator, the pulse widths are controlled and varied in the Figure 14. Moreover, the Figure 14 shows the saturation during 7 sec. The deadzone is also shown after 20 sec. The total firing time of the settling time is about 13.9 sec.

Over all, the two controllers for thruster module are applied to the ACL simulator. All results



(a) History of yaw angle. (b) History of yaw angular rate.

Figure 13. Experimental results of the PWPF modulator for 2 bar pressure.

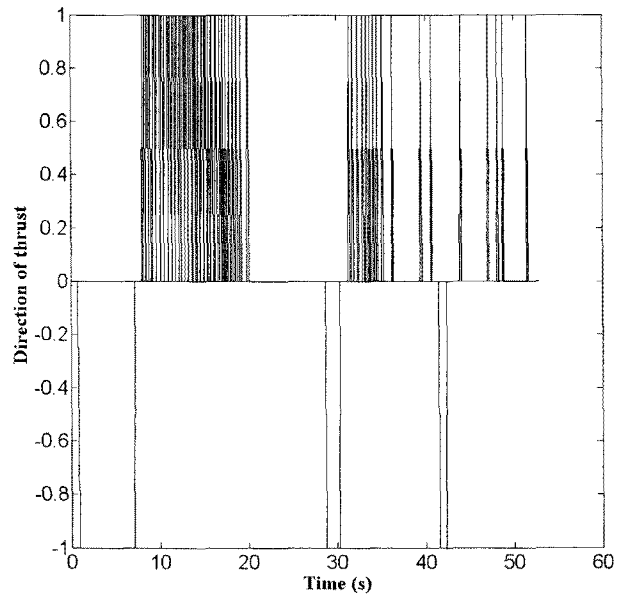


Figure 14. Thrust firing of the PWPF modulator.

show that the angle and angular rate reach steady state response about yaw axis. However, the results show the oscillation during the operation. In this experiment, the initial setting such as mass balancing is not adjusted perfectly. The initial angle of roll and pitch axes are tilted about 0.3~0.5 deg. The difference between the CG and CR, especially about yaw axis, brings out the gravity torque as disturbance. The oscillations in the results are caused by these disturbances. In the results, there is some difference between bang-bang controller and PWPF modulator from the viewpoint of thruster firing. Table 3 shows the comparison of the test results. In summary, the results show that the bang-bang controller has the advantage of the settling time and the PWPF modulator can be applied to reduce the fuel. The PWPF modulator has the superiority of attitude control over the bang-bang control with or without a deadzone. The bang-bang controller uses more fuel and number of firings than the PWPF modulator (Song & Agrawal 1999).

6. Conclusions

In this paper, a HIL (Hardware-In-the-Loop) simulator is designed and developed to extend the ability of validation for the attitude control algorithm. To extend the ability which can validate the attitude control algorithm, thruster reaction control system as additional actuator is designed. The linear actuator for auto-mass balancing is also added. Moreover, the signal flow and power supply are designed to actuate all the system. By using the linear actuator, the center of gravity can be maintained on the center of the Roll and Pitch plane, while only the manual balancing should be applied for Yaw axis. In this paper, the bang-bang controller and Pulse-width Pulse frequency modulator are implemented to the thruster system to control yaw attitude error. The PWPF modulator produces less thruster firing than bang-bang controller. Hence, the required amount of the fuel for attitude control can be reduced by 49% with the PWPF modulator. However, the settling time is longer than that of the bang-bang controller by 22%. Overall, the bang-bang controller has the advantage over settling time, but the required amount of the fuel can be reduced by PWPF modulator. The HIL simulator developed in this paper can be effectively used to validate the control algorithm for the satellite missions.

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