Development of a hardware-in-loop attitude control simulator for a CubeSat satellite

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Abstract. Attitude control is an important part in satellite on-orbit operation. It greatly affects the performance of satellites. Testing of an attitude determination and control subsystem (ADCS) is very challenging since it might require attitude dynamics and space environment in the orbit. This paper develops a low-cost hardware-in-loop (HIL) simulator for testing an ADCS of a CubeSat satellite. The simulator consists of a numerical simulation part, a hardware part, and a HIL interface hardware unit. The numerical simulation part includes orbital dynamics, attitude dynamics and Earth’s magnetic field. The hardware part is the real ADCS board of the satellite. The simulation part outputs satellite’s angular velocity and geomagnetic field information to the HIL interface hardware. Then, based on this information, the HIL interface hardware generates I2C signals mimicking the signals of the on-board rate-gyros and magnetometers and consequently outputs the signals to the ADCS board. The ADCS board reads the rate-gyro and magnetometer signals, calculates control signals, and drives the attitude actuators which are three magnetic torquers (MTQs). The responses of the MTQs sensed by a separated magnetometer are feedback to the numerical simulation part completing the HIL simulation loop. Experimental studies are conducted to demonstrate the feasibility and effectiveness of the simulator.

1. Introduction
Attitude control is a mission-critical part in satellites [1–2]. Thus, it is necessary to be tested to ensure reliable operation in space. However, entirely numerical simulations might not be adequate for testing the flight software/hardware and obtaining any mal-operations.

Hardware-In-the-Loop (HIL) simulation is a real-time simulation technique consisting of a numerical simulation part and a real hardware part. The HIL simulation is nowadays more and more used in variant fields for research and education. The main purposes of the HIL simulation can be grouped into two categories: testing real components [3, 4] and simulating complex systems [5–7].

Examples of HIL simulation applied to space-related systems can be found in [8–10]. In [8], Park et al. developed an integrated orbit and attitude HIL simulator. The simulator can be used to evaluate and verify orbit and attitude synchronous control algorithms, scenarios and relevant hardware technologies for autonomous satellite formation flying. In [9], Corpino and Stesina developed a HIL simulation system used for the verification of functional requirements of a CubeSat. It was shown that the developed system effectively supported the assembly-integration-verification (AIV) process. In [10], Benninghoff et al. used HIL simulation for testing and verifying guidance, navigation and control algorithms for on-orbit servicing of spacecraft. The simulation can effectively simulate variant safe rendezvous test cases.
This work develops a low-cost HIL simulation system used for functional testing of the attitude determination and control subsystem (ADCS) of a CubeSat satellite named KNACKSAT (KMUTNB Academic Challenge of Knowledge SATellite) [11]. KNACKSAT is fully developed in-house in Thailand (see figure 1). The satellite is scheduled to be launched into a 575-km sun-synchronous orbit in 2018. The satellite uses amateur radio frequencies for the communication between the satellite station and ground stations. The KNACKSAT project is funded by Broadcasting and Telecommunications Research and Development Fund for the Public Interest, Office of the National Broadcasting and Telecommunications Commission (NBTC), Thailand.

The objectives of the KNACKSAT project can be categorized into educational objectives and technology demonstration objectives. In term of the educational objectives, the project will enhance the knowledge and experiences in satellite design and construction. These can be considered as fundamentals for development of larger satellites in Thailand in the near future. Apart from these, the project provokes the interests in science and technology of young Thais. For the technological objectives, the main missions of KNACKSAT include (1) developing a communication system using armature radio frequencies, (2) taking images from space, (3) testing 3-axis attitude control algorithms by using magnetic torquers, (4) verifying a deorbit technology by a magnetic torque and (5) confirming the uses of Commercial Off-The-Shelf (COTS) components in space.

Figure 1. KNACKSAT Satellite.

KNACKSAT comprises of six subsystems: Structure Subsystem (STR), Communication Subsystem (COMM), Electrical Power Subsystem (EPS), Command and Data Handling Subsystem (CDH), Attitude Determination and Control Subsystem (ADCS), and Camera Subsystem or Payload (CAM).

Two main functions of the ADCS subsystem are de-tumbling during satellite deployment and attitude pointing. The subsystem consists of three magnetic torquers (MTQ), two three-axis magnetometers, two three-axis rate-gyros and six two-axis sun sensors. The on-board CPU is a 32 bit-microcontroller. The subsystem is summarized in figure 2. More details of the project can be found at http://www.knacksat.space.
The rest of the paper is organized as follows. The description of the developed HIL system is presented in the next section. Experimental setup and results are given in Section 3. The conclusions of this paper are drawn in Section 4.

2. System Description

The main utilization of the developed HIL simulation system is testing the flight software/hardware of the ADCS subsystem of KNACKSAT. The architecture of the system is shown in figure 3. The system consists of a numerical simulation part (indicated by blue-color block), a hardware part (indicated by red-color blocks), and a HIL interface unit (indicated by green-color blocks). The hardware part comprises the ADCS board and three MTQs of KNACKSAT. The numerical simulation part is based on the PROPAT package [12]. PROPAT is a small set of functions in Matlab to simulate and propagate orbit and attitude of an Earth's satellite. The package includes an analytical orbit propagator, allied to a numerical attitude propagator. Also available are functions to compute the position of the Sun relative to Earth and the geomagnetic field in a given satellite position. PROPAT is freely available at http://www.dem.inpe.br/~val/projetos/propat/.

As shown in figure 3, the numerical simulation part outputs simulated satellite’s angular velocity and geomagnetic field information to the ProMini boards through the USB-to-Serial convertor. The ProMini boards representing magnetometers and rate-gyros convert the simulation information to be the corresponding I2C sensor signals, mimicking the signals from the on-board sensors. Then, the signals are fed to the ADCS board. The CPU on the ADCS board reads the signals in the same way as reading from the on-board sensors. By using the information from the read signals, the CPU calculates the control signals based on a predefined control algorithm and then send the control signals to drive the MTQs. The actual magnetic field produced by the MTQs is measured by the magnetometer and then feedback the measured values to the numerical simulation through the DUE board to close the simulation loop. Note that the numerical simulation part uses these measured values to calculate the control torque acting on the satellite.
Figures 4 and 5 display photos of the developed HIL simulator. In figure 4, as indicated by the four red-color circles, the magnetometers and the rate-gyros are not installed on the ADCS board. The cables of the FC signals from the ProMini boards (i.e., simulated magnetometers and rate-gyros) are soldered to the ADCS board substituting the real magnetometers and rate-gyros. In figure 5, the three MTQs are mounted orthogonally in a cube. This mounting configuration is identical to the one on KNACKSAT. The additional magnetometer is installed in the center of the cube, measuring the magnetic field actually produced by the MTQs when they are driven by the ADCS board.

Figure 3. HIL architecture.
3. Experimental Setup and Results
The developed HIL simulator was utilized to verify a detumbling control algorithm on the ADCS board. Satellites are usually tumbling when they are deployed from the launcher. Many detumbling algorithms are available from the literature. The most well-known is the B-dot algorithm [13–15]:

\[ m = -kB \]  

(1)

where \( k \) is a positive gain, \( m = [m_x, m_y, m_z]^T \) is the control dipole moment vector generated by the MTQs and \( B = [B_x, B_y, B_z]^T \) is the geomagnetic field vector measured by an on-board magnetometer. However, the algorithm needs differentiation of the geomagnetic field. The measurement noise in the
magnetometer can cause undesired effects during differentiation. An alternative algorithm to avoid the differentiation is

\[ m = -k(B \times \omega) \]  

(2)

where \( \omega = [\omega_x, \omega_y, \omega_z]^T \) is the angular velocity of the satellite. The angular velocity can be measured directly using an on-board rate-gyro.

The detumbling control algorithm (2) was used here. The numerical solver was the Dormand–Prince method with the step size of 0.1 sec. The control sampling time on the ADCS board was set to be 0.5 sec. The orbit was a circular sun-synchronous orbit with the altitude and the inclination of 575 km and 97.7 deg, respectively. The satellite was assumed to be a rigid body with the inertia matrix:

\[
I = \begin{bmatrix}
0.003340 & 0 & 0 \\
0 & 0.002274 & 0 \\
0 & 0 & 0.003342
\end{bmatrix} \text{km-m}^2.
\]

There are two experiments were conducted here. In the first experiment, the measurement signals (i.e., magnetometer and rate-gyro signals) were assumed to be disturbed by measurement noises. In the other one, the signals were disturbed by both measurement noises and offsets. The initial angular velocity \( \omega_0 = [0.5, 0.5, 0.5]^T \text{rad/sec} \) and the gain \( k = 6000 \) were chosen in all experiments. The gain \( k \) was tuned in numerical simulations such that the tumbling converged within approximately one orbital period (i.e., 5760 seconds) and the magnitude of control dipole moment was less than 0.1 A/m².

**Experiment 1** The zero-mean normal distribution noises with the standard deviation of 3 \( \mu \text{T} \) and 0.02 rad/sec were added to the simulated magnetometer and rate-gyro signals, respectively. These values were choosen cooresponding to setting three standard deviations (3-sigma) equaling to 10% of the maximum operation values of the signals.

The results are shown in figures 6–9. As shown in figure 6, the angular velocities converge within one orbital period. The results for the last 60 sec are shown in figure 7. The control dipole moments are shown in figures 8 and 9. The results indicate that the detumbling algorithm on the ADCS sucessfully detumbling the satellite and the developed HIL simulator is effectively utilized to verify the ADCS hardware and software.

Note that the control dipole moments in figures 8 and 9 are not the values directly calculated from the control algorithm (2). They were the actual values generated by the MTQs. By using these values in the simulation, more realistic results could be obtained since it automatically included transient behaviour, nonlinearity and uncertainty of the MTQs. Our studies also found that the time constant of the MTQs is approximately 0.46 msec, which is considered to be very small comparing to the control sampling period. Thus, the effect of the delay due to the transient behaviour of the MTQs cannot be observed in the simulation. In addition, the control dipole moments were also set to zeros (see figure 9) while the ADCS board was reading the simulated magnetometers. This process is required in real systems to avoid the magnetic fields generated by the MTQs to disturb the magnetometers. The time required to read the magnetometers is approximately 0.2 sec.

**Experiment 2** In addition to the measurement noises as in the previous experiment, the offsets 10 \( \mu \text{T} \) and 0.05 rad/sec were added to the magnetometer and rate-gyro signals, respectively. These values are approximately equal to 10% of the maximum operation values of the signals. The results are shown in figures 10 and 11. As shown in figure 10, the angular velocities still converge within one orbit. However, by comparing to the results of the previous one, there are more oscillations in the angular velocities due to the effects of the offsets.
Figure 6. Satellite angular velocities (Experiment 1).

Figure 7. Zoomed satellite angular velocities (Experiment 1).
Figure 8. Control dipole moments (Experiment 1).

Figure 9. Zoomed control dipole moments (Experiment 1).
Figure 10. Satellite angular velocities (Experiment 2).

Figure 11. Control dipole moments (Experiment 2).
4. Conclusions
This paper has presented a development of a low-cost Hardware-In-the-Loop (HIL) simulator for testing the ADCS subsystem of KNACKSAT satellite. The simulator consists of a numerical simulation part, a hardware part, and a HIL interface hardware unit. The numerical simulation part is based on the PROPAT package. The hardware part is the ADCS board of KNACKSAT satellite. The developed HIL simulator was utilized to verify a detumbling control algorithm on the ADCS board. Experimental results demonstrated the simulator was effectively utilized to test the ADCS subsystem.

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