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A Simple Multi-Mission Flight Control Software for CubeSAT

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ABSTRACT

One of the challenges to date for operational spacecrafts is to satisfy high attitude pointing accuracy missions using picosatellites. This is due to the limitations of putting a capable spacecraft attitude control subsystem into an extremely small volume. To overcome this design constraint, Micro Electrical Mechanical subsystem (MEMS) for attitude sensors and actuators are used. However MEMS are still limited in accuracy and performance compared to conventional sensors and actuators. Given these hardware limitations, the trade off is to increase the software capabilities of the Flight Control Software (FCS) without compromising on a simple architecture concept. Astronautic Technology Sdn. Bhd. (ATSB)™ is currently developing a $10x10x30cm^3$ CubeSat capable of meeting missions requiring spinning or full three axis stabilization. The Attitude Determination and Control (ADCS) suite consist of a MEMS 3-axis magnetometer, three 1-axis gyroscopes, coarse sun sensing capabilities, magnetic torque coils, a pitch actuator and the well known 8051 microprocessor housing the FCS. The 8051 communicates with the master MSP430 onboard computer via a Serial Peripheral Interface (SPI). An alpha version of the FCS was developed and tested on an 8051 board. The FCS was compiled using a commercial Integrated Development Environment (IDE) and loaded directly onto the 64KB on-chip flash. The software consist of a single axis Spin control law for regulating the spin rate on any predefined axis using only magnetic torque coils. A single axis Proportional Derivative (PD) control law was also developed to manage 3-axis slew maneuvers using a mini reaction wheel and magnetic torque coils. The 8051 board was linked via RS232 to a test PC running the full spacecraft orbit and attitude simulation in real-time, i.e. Hardware-in-the-Loop (HIL). The FCS was able to detumble the CubeSat, bring it to the designed pitch spin axis, achieve 3-axis stabilization and perform 3-axis maneuvers. This simple setup allows the FCS to be designed, debugged and performance tested quickly. The FCS has been validated to meet CubeSat's current spinning and limited 3-axis pointing mission requirements.

INTRODUCTION

The introduction of CubeSats paved the way for a new generation of affordable and standardized picosatellites for academia, where universities, schools and even several small companies around the world have developed their own version of CubeSats, ranging from 1U ($10x10x10cm^3$) to 3U ($10x10x10cm^3$) in size. Mass and volume limitation have challenged designers to pack as much technology as possible to meet specific mission needs. To date the missions are limited to scientific measurements and remote sensing instruments with wide attitude pointing requirements, mainly due to the limited Attitude determination and Control Subsystem (ADCS). Almost all CubeSats have Magnetometers and Magnetic Torque Coils to detumble and stabilize the satellite after separation from the P-POD deployer. Recently a CubeSat, ION[1] developed had additional micro-vacuum arc thrusters, where for the first time, it was possible to provide 3-axis pointing maneuvers in a small platform.

On a similar path, ATSB™ embarked on the development of a CubeSat capable of performing multi-missions. From experience, most missions can be catered by two types of attitude modes, i.e. spinning and 3-axis pointing. The design philosophy is to achieve these two modes using a simple ADCS software, i.e. the Flight Control Software whilst maximizing the usage of modest sensors and actuators.

ATTITUDE SUBSYSTEM SUITE

The baseline ADCS suite for ATSB™'s CubeSat consist of commercial Micro Electrical Mechanical Subsystem (MEMS) sensors, i.e. a 3-axis Magnetometer and three single axis Gyroscopes. Coarse Sun vector measurements shall be determined from solar cell telemetries located on each face of CubeSat that are primarily used for power generation. Three magnetic torque coils shall provide 3-axis stabilization.

By incorporating control laws like the well known B-dot[2,3] and LQR[4], detumbling and stabilization of a boomless CubeSat are achievable using the cross product of a generated dipole *M* in a magnetic field *B* to generate torque *T*. However, due to the singularity of the *B* matrix when inverted[5], the exact required dipole to generate the necessary torques for 3-axis pointing maneuvers cannot be achieved. The solution for stabilization, as suggested by Sidi is to place one momentum wheel in the body pitch axis (Y-axis) as shown in Equation 1.

$$\begin{bmatrix} T_{Bx} \\ T_{By} \\ T_{Bz} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -B_y \\ -B_z & 1 & B_x \\ B_y & 0 & 0 \end{bmatrix} \begin{bmatrix} M_x \\ \dot{h}_{wy} \\ M_z \end{bmatrix} \qquad (1)$$

Where $\dot{h}$ is the rate of change of wheel momentum. This concept is used in ATSB™'s CubeSat and requires the development of a mini reaction wheel instead for pointing maneuvers.

The core of the ADCS is an 8bit address wide 8051 microprocessor running at 16MHz with 64kB of programmable flash memory and 4352 bytes of internal data RAM. The microprocessor houses the Flight Control Software (FCS) and handles all interfaces to the ADCS sensors and actuators as well as interfaces to CubeSat's MSP430 Onboard Computer (OBC).

FLIGHT CONTROL SOFTWARE

The FCS termed here is the entire software that overseas all ADCS related function. It consist of the software modules as shown in Figure 1. A description of each module is given in the following sections

Initialization

The Boot Loader termed here only determines the starting address and loads new program applications and calibration tables from the OBC during in-flight. Initialization contains all the necessary codes to initiate the microprocessor after power-up or reset.

Real Time

The FCS operates close to real time by running as a scheduler. The main timer is set to overflow at 10milli-seconds and the schedule repeats every 1000milli-second, to allow time for all functions to execute. Hence the Control bandwidth is 1Hrtz and is sufficient to meet a broad range of mission requirements and

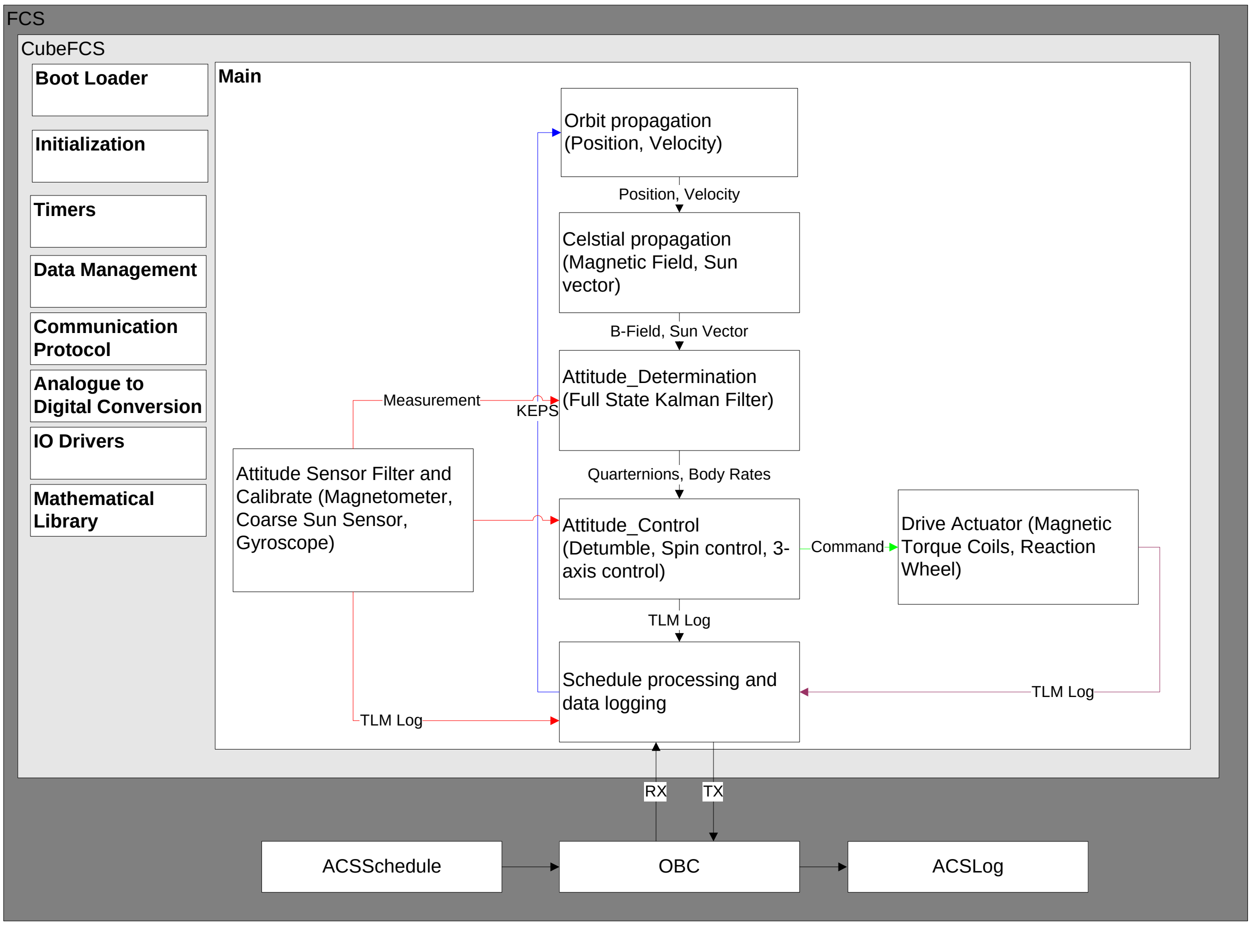

Figure 1: FCS Software Modules and Main Flow Diagram

overcome any low frequency disturbances. The timers are synchronized with the OBC timer.

Interface

The ADCS microprocessor is a Slave to the Master OBC via Serial Peripheral Interface (SPI) bus at 1MBps. Communication of ADCS to other subsystems is overseen by the OBC. A UART is setup to allow communication with other subsystem or components that have their own dedicated microprocessor. A secondary UART is routed through an RS232 circuit and link to the PC for FCS testing via a HyperTerminal.

Sensors filtering and calibration

The MEMS Magnetometer and Gyroscopes produce analogue telemetries that are sampled by the on-chip 12-bit Analogue to Digital Converters (ADC). The FCS also over samples and averages the telemetries and convert the raw data to calibrated data. The telemetries from the solar cells are sampled by the Electrical Power Subsystem (EPS) and hence is directly fed into the microprocessor.

Driving Actuators

The Magnetic Torque coils are driven by a relay circuit activated by the General Purposes Input Output (GPIO) pins of the microprocessor. The mini reaction wheel has a dedicated microprocessor to handle wheel speed control and hence communicate with the ADCS microprocessor via UART.

Control Law

There exist two control laws that are sufficient to meet CubeSat's spinning and 3-axis pointing mission requirements. These are the Spin control law and the PD control law.

The Spin control law is a combined B-dot and a single axis Thompson mode control law. This control law was used in UOSAT-12[3] for a Y-Thompson mode stabilization. The same control law is applied to CubeSat to detumble the satellite after P-POD deployment and spin the satellite to a commanded pitch body rate to achieve gyroscopic stiffness. The pitch axis (Y-axis) is the Y-Thompson spin axis and both the roll (X-axis) and yaw (Z-axis) body rates are reduced to near zero, all regulated by the Spin control law. The control law only requires body rate information that is provided by the Extended Kalman Filter. The Spin control law is also simple to implement and can be operated not only in detumbling, but also in nominal and safe-hold satellite modes. The Spin control law is given as follows.

$$\begin{aligned} M_x &= K_s\left(\omega_{yo} - \omega_{yoref}\right)sign\left(B_z\right) \\ M_y &= K_d\left(\arccos\left(\frac{B_y}{\|\mathbf{B}\|}\right)\right) \\ M_z &= K_s\left(\omega_{yo} - \omega_{yoref}\right)sign\left(B_x\right) \end{aligned} \tag{2}$$

Where M_i is the generated moment, K_s is the spin gain, K_d is the detumbling gain, B_i is the geomagnetic field and ω_{yo} is the pitch body rate with respect to orbit reference.

For 3-axis pointing control, as introduced by Equation 1, placing a reaction wheel produces a decoupled roll and yaw torque upon generation of the roll or yaw dipoles. However, the cross coupled torques about the pitch axis still exist when these dipoles are generated. This is then compensated by the reaction wheel that also generates the pitch torque. The semi-novel controller proposed for CubeSat is a combined Proportional Derivative (PD) control law that governs the mini reaction wheel as well as the roll and yaw torques using a cross product control law. This provides full 3-axis control and 3-axis pointing can be performed.

For small angles the PD control law for the reaction wheel is given as follows:

$$T_y = -\left(K_p q_{e2} + K_d \omega_{yo}\right) \tag{3}$$

Where K_p and K_d are the gains and q_{ei} is the quaternion error of the commanded and current satellite attitude.

The PD cross product law for roll and yaw axes is as follows.

$$M = \frac{e \otimes \mathbf{B}}{\|\mathbf{B}\|}, \quad \begin{aligned} e_x &= K_p q_{e1} + K_d \omega_{xo} \\ e_y &= 0 \\ e_z &= K_p q_{e3} + K_d \omega_{zo} \end{aligned} \tag{4}$$

Full details of the Spin and PD control law derivation shall be explained in a future paper.

Estimator

A full state Extended Kalman Filter (EKF) is used to provide estimated attitude quaternions and body rates in the orbit reference frame. The full state EKF is not discussed in this paper and only the main points are highlighted as follows.

For a given time step, the 7 element state vector is given as:

$$x = \begin{bmatrix} q^T & \omega_b^{o\ T} \end{bmatrix}^T \qquad (5)$$

The innovation is given as follows:

$$e = v_{meas} - A[\hat{q}]v_{orb} \qquad (6)$$

Where v_{meas} is the measured vectors from the Magnetometer and Coarse Sun Sensor and v_{orb} is the reference vector generated by the IGRF and the Sun vector model. The standard EKF algorithm is applied and the process noise covariance matrix, given the sensor noise covariance, is fine tuned to achieve fast convergence of the filter. When more accurate MEMS sensors are developed, the innovation can be increased to include these sensors and hence increase the accuracy of the estimation.

HARDWARE-IN-THE-LOOP

The control and estimators were simulated in a full orbit and attitude simulator running on a PC. The simulator consist of an orbit propagator, celestial mechanics for IGRF and sun vector calculation, disturbance models, spacecraft dynamics, kinematics models, sensor and actuator models. Both the control laws and estimator performed as expected in the simulation.

The next step is to validate the simulation by actually running the control laws and estimator on the 8051 microprocessor. This is accomplished by using a commercial Integrated Development Environment (IDE) containing a commercial x51 assembler, compiler and linker. The FCS code was compiled and linked to create target specific code that is then downloaded onto the 64KB on-chip flash of the microprocessor via a JTAG. With proper data management and using a small memory model, a compact FCS is created. By setting up the secondary UART, RS232 circuit, the ADCS microprocessor can replace the control and estimation block in the simulator, setting up a Hardware-in-the-Loop (HIL). The microprocessor executes the FCS in real time and the simulator provides the simulated model of the orbit, space environment sensor model measurements, actuator model and spacecraft dynamics, as shown in Figure2. The immediate download enables rapid prototyping, debugging and test of the FCS on the microprocessor, beginning with specific software modules and later as an integrated software.

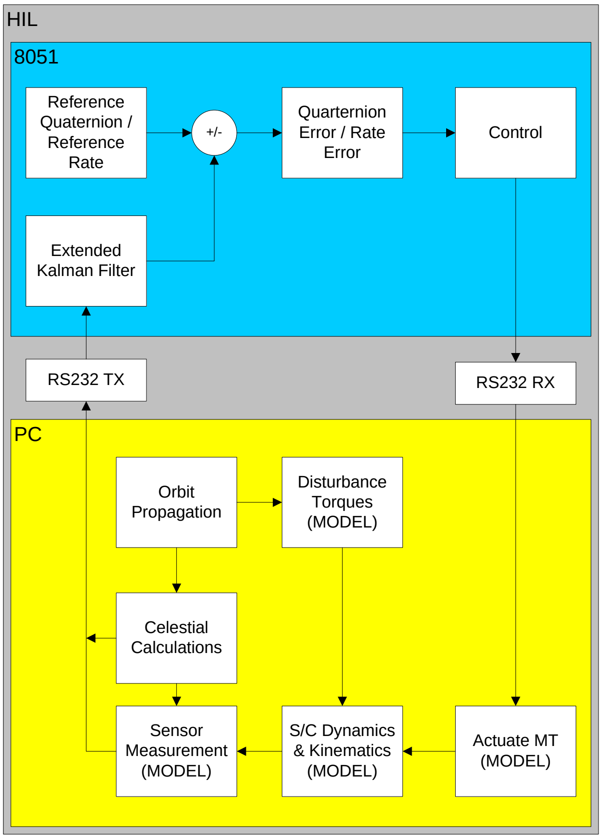

Figure 2: Block diagram of Hardware-in-the-Loop

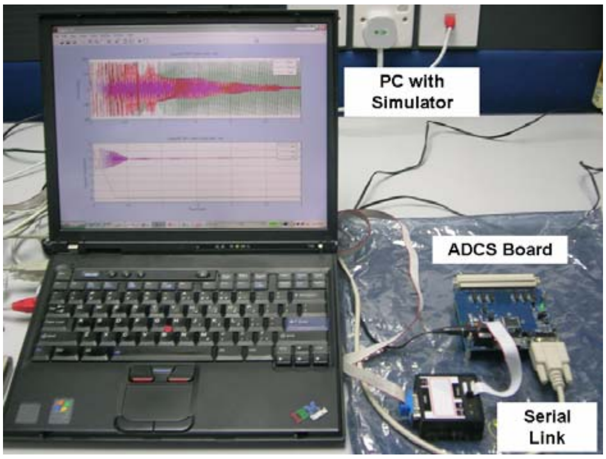

Figure 3: Actual Hardware-in-the-Loop Setup

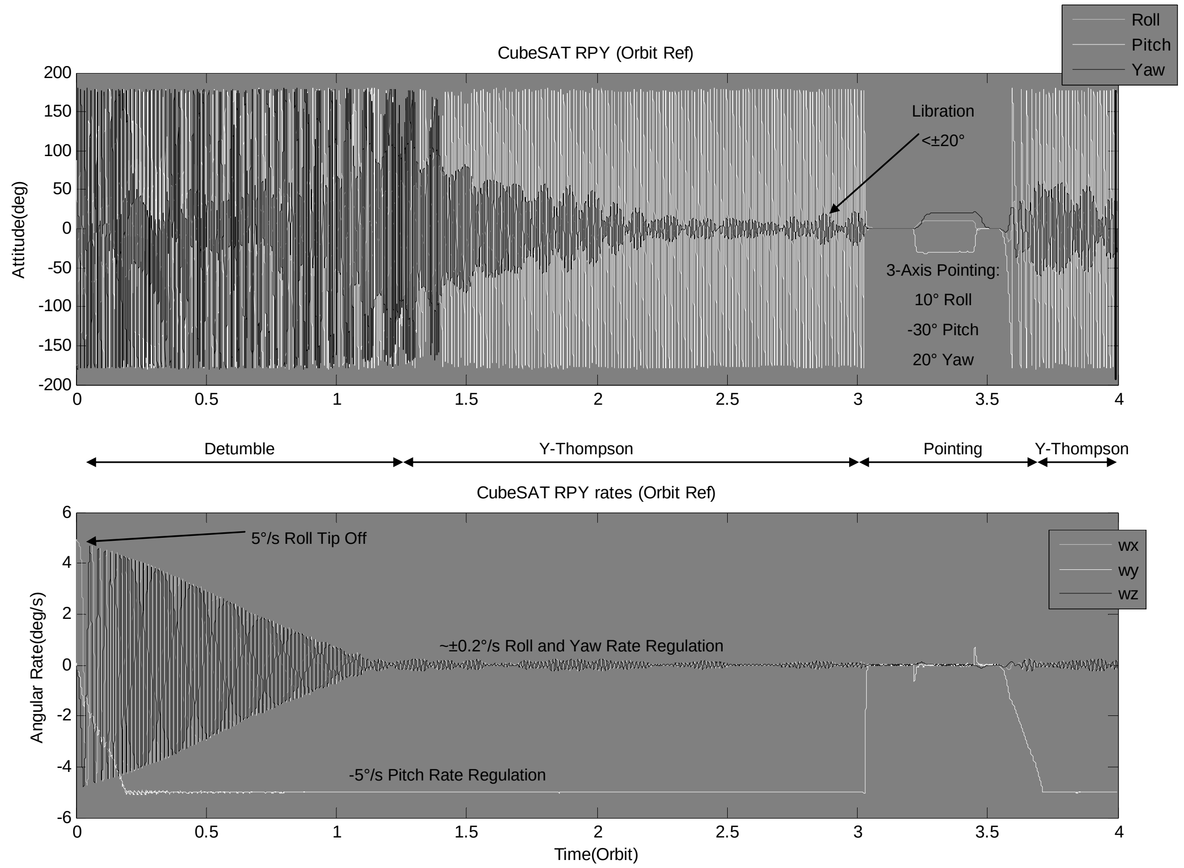

Figure 4: Emulation performance of CubeSat from detumbling to 3 axis pointing

PERFORMANCE

The HIL test was implemented for a scenario from separation to 3-axis pointing for a circular orbit with 9° inclination and 685km altitude using CubeSat's estimated Moment of Inertia. As seen from Figure 4, CubeSat was detumbled by from a roll tip-off body rate of 5°/s and reached Y-Thompson Mode with a desired regulated pitch rate of -5°/s and achieved about ±0.2°/s for both roll and yaw rates using the Spin control law. The satellite librated not more than ±20°/s in this mode with the existence of disturbance torques. This is an acceptable performance.

Prior to the 3rd orbit, the Spin control law was switched off and the full state EKF was turn on. At the 3rd orbit, the PD control law was switched on and with a command of 0° roll, pitch and yaw, CubeSat achieved Nadir pointing from Y-Thompson, i.e. the body Z-axis aligned with the orbit Z-axis reference frame. A slew maneuver was then performed by commanding the satellite to point at an arbitrary reference of positive 10° roll, negative 30° pitch, and positive 20° yaw. All three axes achieved the desired command attitude with errors less than 0.5° within 0.08orbits as shown in figure 5. CubeSat was then commanded back to Nadir pointing. The full state EKF was switched off and the controller was switched back to the Spin control law to resume Y-Thompson mode.

The FCS, more precisely both the control laws, on the microprocessor performed well. Although the HIL 3-axis pointing are less than 0.5° for all axes, further development and optimization of the FCS is required as the actual performance of the physical MEMS sensors and actuators have yet to be determined and calibrated. Hence a more realistic pointing error is expected to be not more than 1°.

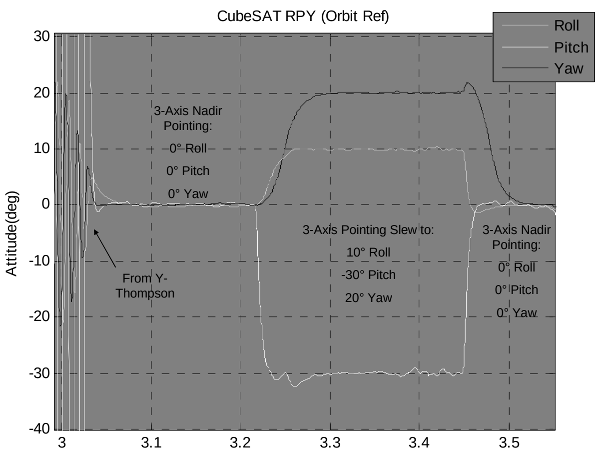

Figure 5: 3-axis pointing performance of CubeSat

CONCLUSION

The initial development of a simple FCS, using well known control laws and estimators have shown to perform in real time on the 8051 microprocessor using the HIL setup. Currently the FCS is an alpha version and the full FCS shall be tested once all software modules are developed and ported to the microprocessor. The FCS is expected to cater for CubeSat missions requiring spinning and/or 3-axis pointing capabilities. Hence multiple missions such as target remote sensing, target tracking, communication pointing, pointing of science instruments to celestial objects and formation flying are possible. The simplicity here is that it only requires fine tuning the gains of the Spin and PD control laws and the EKF estimator to cater for specific missions and by using the HIL setup, the entire FCS can be validated quickly and efficiently.

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