SSC17-WK-09

Methodology for Software-in-the-Loop Testing of Low-Cost Attitude Determination Systems

Stephanie Wegner, Evan Majd, Lindsay Taylor, Ryan Thomas and Demoz Gebre Egziabher
University of Minnesota – Twin Cities
107 Akerman Hall, 110 Union St SE, Minneapolis MN 55455; 612-518-4798
wegne135@umn.edu

ABSTRACT

Proper functioning of attitude determination systems is indispensable to many CubeSats. Avoiding failure in these systems is paramount to the success of these missions. To increase on-orbit reliability, extensive testing of attitude determination systems testing in a representative operational environment is necessary. However, a survey of the relevant literature on CubeSat attitude determination systems using low-cost gyroscopes and magnetometers shows a lack of extensive system-level testing documentation. To address this shortcoming, this paper discusses the development of easily implementable software-in-the-loop testing procedures for CubeSat attitude determination systems. The proposed approach uses a Helmholtz cage to simulate the on-orbit magnetic field environment. The outlined procedure tests an attitude determination algorithm that uses data from 3-axis magnetometers, 3-axis gyroscopes and GPS. This paper describes the test procedure, provides attitude determination test results obtained using the developed methodology, and suggests improvements for future systems.

INTRODUCTION

CubeSats are small and relatively inexpensive satellites whose structure is constructed, by concatenating a basic cubic structural module which is approximately 10 cm x 10 cm x 10 cm in dimension with a mass of 1.33 kg[1]. This basic building block is referred to as 1 CubeSat unit or 1U for short. The majority of CubeSats launched to date or envisioned for launch are 12U or less in volume, and thus fall in the category of spacecraft normally referred to as microsats. As such, all the challenges associated with designing reliable Guidance, Navigation & Control (GN&C) systems for microsats are shared by CubeSats and stems, primarily, from the severe size, weight and power (SWaP) constrains. In addition, since many CubeSats are being developed by entities with limited resources and budgets relative to traditional aerospace organizations (e.g. educational institutions, small companies, etc.), cost of development and testing is another significant constraint[2, 3].

The severe SWaP and cost constrains have been the impetus for intense research and development work into devising novel attitude determination and control schemes for space applications. The combination of novel systems (i.e., limited flight heritage) developed on tight budgets and with accelerated schedules are prescription for failure. For example, data compiled in[4] shows that nearly 50% of all first-time university CubeSat missions end in failure. The primary contributors to known failures are power system, communication system and flight computer system malfunctions. Attitude determination and control system failures contribute to about 3% of all failures for the so-called "dead on arrival" CubeSats. These are CubeSats that are non-operational when they arrive on orbit.

While it may seem that attitude determination and control system failure are not a primary driver of failures, this conclusion is misleading. First, most attitude determination and control systems on CubeSats are not very complex. As CubeSat technology matures, complex attitude determination and control systems will start being used which may increase the likelihood of failure. If this is not accompanied by increased reliability, the 3% figure is likely to increase. Second, a large number of CubeSat failures noted in[4] are due to "unknown" causes, and thus may be due to failed attitude determination and control systems.

These sobering statistics are, in part, the motivation for the work described in this paper. At present, there are few, if any, *inexpensive* methods for end-to-end testing of CubeSat attitude determination and control systems. This is particularly true when it comes to attitude control systems. The focus of the work described here is on attitude determination and method for testing them inexpensively. We describe a method that will allow testing attitude determination algorithms and systems up to and including software-in-the-loop, and perhaps hardware-in-the-loop testing as well.

Accordingly, the remainder of this paper is organized as follows: First the overall approach and philosophy to designing and testing low cost attitude determination systems is described. Next, the low-cost approach for doing this is described. A summary and concluding remarks including suggestions for future work and improvements close the paper.

SYSTEM DESIGN PROCESS

The general approach for designing, testing and validating low cost attitude determination systems follows a series of steps. The first step consists of developing a set of requirements for the attitude determination system. This includes specifying performance requirements such as the required solution accuracy. It also includes putting limits on overall system cost, weight, power consumption and size or the so-called SWaP constraint.

Once the requirements are in place the conceptual design phase commences where a “paper” design of the system is developed. This includes identifying specific hardware (sensors, processors, etc.) as well as developing an algorithm. In addition, a simulation environment is developed that allows testing and validating the algorithm developed. Usually, software tools such as MATLAB or Python are used to prototype the attitude determination algorithm in this phase.

Once the conceptual design phase is complete, the next step is to translate the MATLAB or Python-based algorithm into the language that will used on the embedded system computer that will eventually host and run the attitude determination algorithm in real-time. Once translated, a software-in-the-loop (SIL) phase of the design commences. SIL requires having access to a simulation environment which has the facilities for generating simulated sensor inputs with error characteristics that match the sensors that will be used on the actual system. SIL testing is used to detect issues such as algorithm flaws and the ability of the algorithm to keep-up with generating an attitude solution in real-time.

After SIL, the hardware-in-the-loop (HIL) phase begins. HIL testing requires that a prototype of the attitude determination system hardware be available. At a minimum, this means that an embedded processor running a real-time operating system has been identified. The algorithm validated in SIL is ported over to the embedded processor. Furthermore, the sensors that will be generating the observables used by the attitude determination algorithm will have been identified. The sensor and embedded processor will be packed into a suitable form factor that will allow moving them as a unit through a series of attitude maneuvers simulating motion of an actual CubeSat. The outputs of the HIL are analyzed to confirm whether the attitude determination system is working in real-time with a performance consistent with the system requirements.

In the current environment, it is difficult to do this inexpensively for CubeSats. The approach described in this paper is an attempt to allow attitude determination system design and testing to be accomplished in a low-cost manner with a reasonable amount of fidelity. There is a large body of literature describing attitude determination algorithms, and thus we will not discuss that in any detail in this paper. Rather, we will describe the SIL infrastructure developed to enable low cost testing of CubeSat attitude determination systems.

SIL TESTING INFRASTRUCTURE

To enable SIL testing, we elected to start with the PixHawk flight control system and modifying as required. The PixHawk is an inexpensive flight control system designed around a low cost IMU, magnetometer triad and GPS that is used widely in the Uninhabited Aerial Vehicle (UAV) market. It is a low-cost system with an extensive open source library of algorithms.

Figure 1 shows a photograph of the PixHawk hardware. It is an 81.5 mm x 50.0 mm x 15.5 mm flight computer comprising of three important inertial sensors: accelerometers, magnetometers, and gyroscopes (each of these sensors being 3-axis capable). The gyroscopes specifically the ST Micro L3GD20H 16-bit gyroscope, measure angular rates in three perpendicular axes. This is MEMS based with an I2C/SPI digital-output interface. The accelerometers and magnetometers measure acceleration and magnetic field, respectively. They are specifically the one package ST Micro LSM303D 14-bit accelerometer/magnetometer and are also an I2C/SPI digital output interface. The magnetometer has a magnetic sensitivity of .08 mG/LSB and a magnetic cross axis sensitivity of +/- 1 %FS/Gauss. FS is the measurement range of the magnetometer in Gauss.

Figure 1: PixHawk flight control system

There are two versions of flight control system software that run on the PixHawk. We elected to use what is known as the PX4 flight stack. The PX4 flight stack consists of numerous modules for attitude determination, navigation, guidance and control of small UAVs. Each module is an application that gets launched when the PixHawk is powered on. The modules are designed around the subscribe-and-publish model. Any module that requires a particular sensor's data will subscribe to that information. The output of each module, in turn, is published in such a way that other modules have access to them. For example, there is an application that generates a navigation solution by fusing the IMU and GPS measurements using an Extended Kalman Filter (EKF). This module subscribes to IMU and GPS sensor outputs and publishes its solution (attitude, velocity and position estimates) to a data structure that is accessible to other modules.

To allow SIL testing of CubeSat attitude determination algorithms, we designed a new module that runs in the PX4 flight stack. This module is effectively a software "sandbox" that subscribes to all sensor outputs and can publish its output to data structure shared by other modules. The developer of a CubeSat attitude determination algorithm can write an algorithm in C or C++ in this "sandbox." Once compiled, the extensive simulation infrastructure that comes with the PX4 flight stack can be used to perform SIL testing.

However, the simulation environment for the PX4 does not support space environments. That is, it does not allow simulation of sensor outputs that would be seen on orbit. While there is work underway to develop a simulator environment to support this feature, at the moment a Helmholtz cage with a turning table was used to generate signals that are somewhat like those that would be seen on orbit. One Helmholtz cage test performed that most closely resembled the satellite on orbit was when a magnetic field was rotated about an axis at the same time as the flight computer was rotated about the same axis. For the purposes of testing, the flight computer's measured acceleration (gravity vector) was used to emulate a second vector (e.g., line of sight to the sun as would be generated by a sun sensor) and saved for evaluation of the attitude determination algorithm later. The gyroscope and magnetometer measurements were used as recorded during testing and used in SIL evaluation.

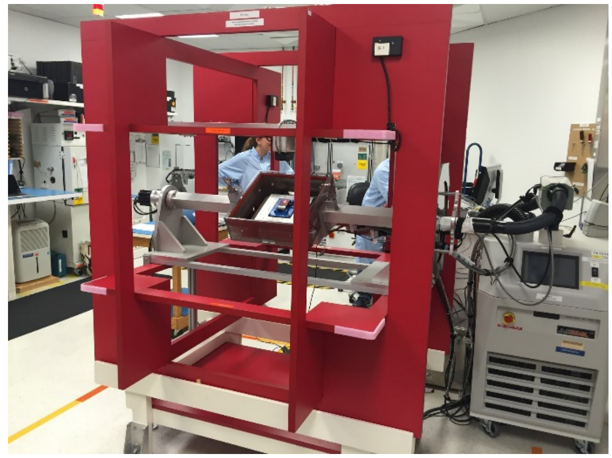

Figure 2: Helmholtz cage setup

The Helmholtz cage used is shown in **Figure 2**. The rotating plate shown in the middle of the figure is where the flight computer was mounted during the testing. An adapter plate which allows easily mounting the PixHawk flight computer to the rotating plate was 3D printed. The adapter plate is shown in **Figure 3** and allows quick installation and removal of the flight computer from the Helmholtz cage.

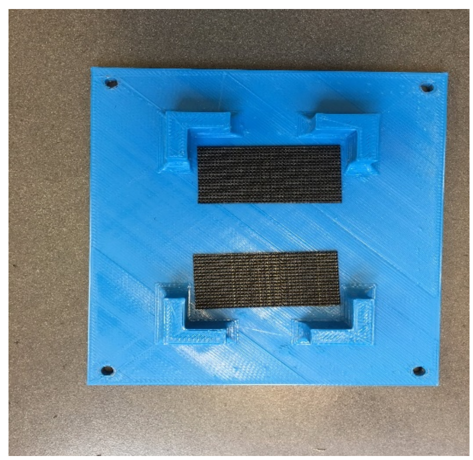

Figure 3: PixHawk adapter plate

SENSORS CALIBRATION

The attitude determination algorithm developed and used in the work described here fuses the information from a triad of rate gyros, triad of magnetometers and a GPS receiver using an extended Kalman Filter (EKF). The EKF gain matrix is a function of the uncertainty (error) model of the sensors used. Thus, one part of the design of the attitude determination system is performing an accurate characterization of the sensors so that their error characteristics can be modeled. In what follows we describe characterization of the rate gyro and magnetometer error models.

Rate Gyro Error Models

There is an extensive body of literature describing methods for developing rate gyro error models (especially for low cost systems). As such, we will not dwell on this aspect of the work here. It is sufficient to note that reasonable error models can be developed by collecting long-term output from a gyro triad subjected to zero inputs. This allows generating an estimate for output noise, null shift and in-run bias stability—the three key parameters that characterize the performance of any rate gyro. The static data used for this error model development can be collected at the same time magnetometer data is being collected for calibration.

Magnetometer Error Model

In low cost attitude determination systems or those used on CubeSats present a unique challenge with respect to magnetometers. Since the magnetometers are part of a sensor package, and thus placed in close proximity of other potentially magnetic materials and current carrying wires by design, they will be subject to a bias that cannot be eliminated by relocation of the entire sensor package. Thus, the magnetometer calibration involves characterizing any residual fields that may be present due to the installation of the magnetometers in the sensor package. These errors were characterized using measurements taken in a zero-gauss chamber. Other errors were evaluated using the Helmholtz cage as a whole.

Figure 4 shows the multi-layer zero-gauss chamber used. It was made from a soft magnetic alloy that works to cancel out any static or slow-changing magnetic fields, known as μ-metal. Both a three-layer and five-layer chamber were used for comparison of results. For most of the tests, the zero-gauss chamber was used for sensor calibration within the Helmholtz cage by matching the readings in the chamber to those seen in the Helmholtz cage when it was set at "zero" (known as the offsets set in the Helmholtz cage).

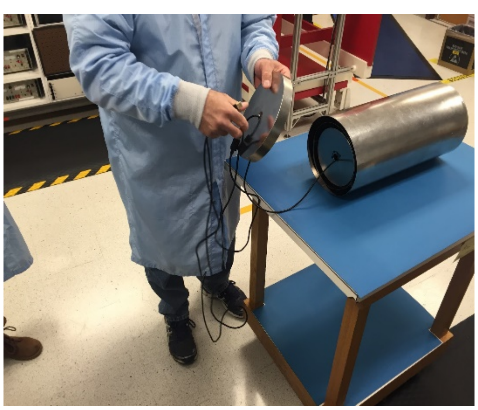

Figure 4: Multi-layer Zero Gauss Chamber

Figure 5 shows some of the results obtained from this testing for the magnetometers. What is shown is the magnetometer output in the zero-gauss chamber. These traces allow characterizing the constant and time varying nature of the output noise and bias of the magnetometer triads.

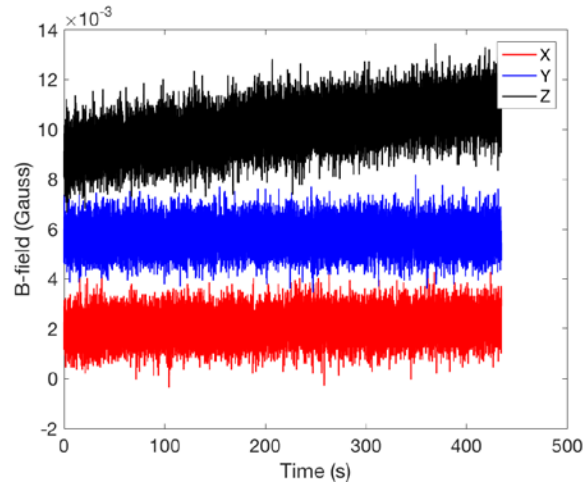

Figure 5: Magnetometer readings from Zero Gauss Chamber with the cap on

SIL EVALUATION RESULTS

The attitude determination system to be evaluated was initially prototyped in Simulink™ and then Python. It is based on an adaptation of an existing algorithm[5]. Once the algorithm was found to be performing acceptably, it was translated into C-code suitable for the embedded processor found on the PixHawk.

This process of translating the algorithm from Python (or Simulink™) to C-code revealed/identified issues that could not have been seen in simulation only. For example, it was found that the code as written in Simulink™/Python required more memory than was available on the embedded processor. This required implementing numerical "tricks" to simplify certain matrix operations and re-declare some variables as types that did not require a large amount of memory (e.g., change loop counters from signed ints to chars, etc.).

Note that on orbit, the magnetic field vector of the Earth will change as a function of the CubeSat's position. However, for testing on the ground outside of the Helmholtz cage, the Earth's magnetic field vector will be time invariant. This will cause the attitude solution to diverge because the filter becomes unobservable. To get around this issue the measurements of Earth's gravitational vector from the accelerometers was used as a second vector. Future testing in the Helmholtz cage is planned where the magnetic field will change consistent with what would be seen on orbit and thus, provide a more accurate SIL testing of the algorithm.

The following figures show the output of the SIL testing of the attitude determination algorithm. The histograms show the attitude errors for 20 runs of the attitude determination system. Each test lasted 1.5 minutes with the attitude filter running at 100 Hz. The attitude solution is assumed unknown at the start of the SIL runs and thus, set to zero. The attitude determination algorithm determines the attitude on its own, taking about 30 seconds for the solution to converge. Once the solution has converged, the difference between the attitude solution computed and those generated by the ground-truth system (a second attitude determination system mechanized as a classic INS/GNSS filter) are computed. The histograms below show the results for this comparison parameterized in terms of Euler angle errors. This is done for visualization only, as the attitude solution in the actual filter is parameterized in terms of quaternions so that gimbal-lock is a non-issue.

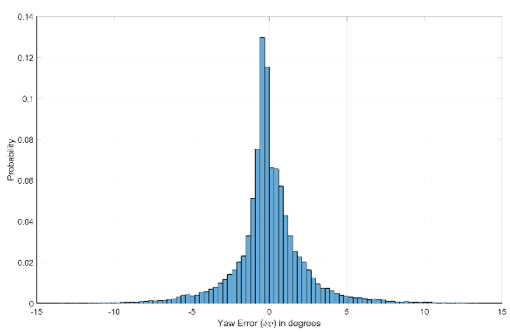

Figure 6: SIL simulation yaw error

From the plots shown in Figures 6 through 8 we can see that the 2σ attitude errors (95% confidence bound) are as follows: $7.318°$ for yaw, $3.749°$ for pitch, and $7.112°$ for roll. This attitude determination system is being developed in support of two CubeSat missions for which the requirements are that attitude errors be less than $25°$. Therefore, at this stage of development, the attitude determination system under design will satisfy the mission requirements.

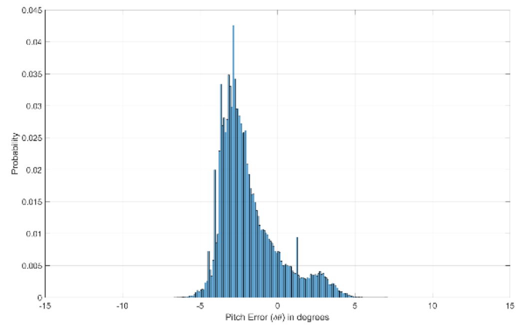

Figure 7: SIL simulation pitch error

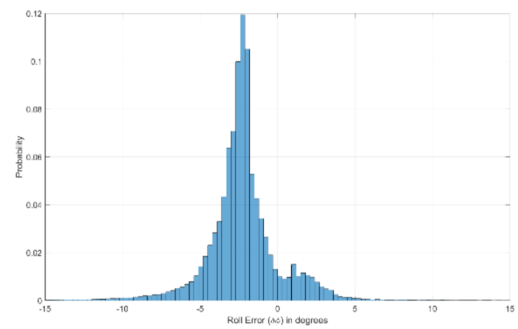

Figure 8: SIL simulation roll error

CONCLUSION

Attitude determination systems can be critical components in a small satellite's functionality in orbit. Testing of these systems can be difficult and expensive due to the necessity to simulate orbital parameters, such as GPS location, magnetic field, and gyroscopic rates. A method for using an off-the-shelf UAV flight control systems for software in the loop testing of CubeSat attitude determination systems was presented. The approach used a software "sandbox" to allow testing of real-time attitude determination software. A method for further testing in more realistic, orbit-like environment using a Helmholtz cage with a rotating plate was also described. The Helmholtz cage and rotating plate were also used to characterize the low-cost sensors, which is beneficial when not all sensor specifications one needs are published on the specification sheet. Overall, the use of a Helmholtz cage and rotating plate was shown to successfully test an attitude determination system. These tests can be applied to many other small satellite missions and attitude determination algorithms, as it provided or simulated all orbital parameters required.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the following individuals and organizations for providing support for the work reported in this paper: Mr. John Weyrauch, Dr. William Garrard and Dr. Lindsay Glessener (University of Minnesota, Twin Cities); Honeywell International Inc (Mr. Mike Freeman); the Minnesota Space Grant Consortium; the United States Airforce University Nanosat Program; NASA Office of Education; and the UAV Laboratory at the University of Minnesota. However, any opinions, findings, conclusions, or recommendations in this paper are those of the authors and do not necessarily reflect views of any of the above persons or organizations.

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