Introduction

We are developing design techniques and sensor calibration algorithms that enable the rapid development of small spacecraft while maximizing the accuracy of low-cost sensors used within the spacecraft. This work is presented here as an example of the attitude determination and control subsystem, but many of the principles can be extended to other subsystems as well. These methods have been applied to satellites developed by the Michigan Exploration Laboratory (MEL), and continue to be improved using lessons learned from their application in the design and operations of small spacecraft. These development lessons and design techniques result from our focus on sensor orientation optimization. These methods can be used to significantly improve the performance of small satellite attitude determination systems, such as the MEL-developed subsystem shown below.

Small satellite attitude determination subsystem design and development

The Radio Aurora Explorer (RAX) satellites are 3U CubeSats developed by MXL to study space weather. A custom attitude determination system was developed for RAX, and is currently being upgraded for the next generation of MXL spacecraft. The subsystem utilizes photodiodes for sun sensing, multiple three-axis magnetometers, and a three-axis rate gyroscope; all are off-the-shelf components. The subsystem has demonstrated accuracies of between 2° and 4° (1-σ) on the RAX-1 spacecraft.

Magnetometer calibration: Removing satellite-induced magnetic fields

Magnetometers are a common sensor for attitude determination in low earth orbit because of their simplicity and low cost. However, their accuracy in measuring Earth’s magnetic field can be severely impeded by the time-varying magnetic fields produced by on-board electronics. Traditionally, this error is mitigated by physically separating the magnetometer from the spacecraft with a boom or by designing and manufacturing practices to maintain the magnetic field produced by circuit electronics. Both of these methods increase spacecraft development costs and time, as well as reducing the potential lifetime for small spacecraft.

We have developed a method for on-orbit, attitude-independent magnetometer calibration that mitigates the effect of nearby electronics. In application to the RAX-1 spacecraft, the technique reduced the magnetometer angular accuracy by an order of magnitude, and increased the accuracy of the measurements to the accuracy of the stand-alone sensor.

The calibration method works by including measured currents in nearby electronics in the magnetometer measurement model. The current measurements are mapped to the corresponding magnetometer bias by parameters estimated in the calibration process. The calibration also includes bias, scaling, and non-orthogonality, and it is carried out using flight data without the need for attitude knowledge. RAX-1 data from before and after the calibration is shown in the plots. The accuracy of the measurements with the magnetometer minus the bias has improved by an order of magnitude, and increased the accuracy of the measurements to the accuracy of the stand-alone sensor.

Design methods for optimal configuration of directional sensors

Photodiodes are a common method of sun sensing on small spacecraft. Photodiodes produce a current as a function of the angle between their normal direction and line of sight to the sun, and multiple photodiodes must be combined to obtain a unique sun vector measurement. The uncertainty contributed by the sun vector measurement depends on the performance of the individual photodiodes as well as the orientation of the photodiodes.

We have developed a formulation to find photodiode configurations that minimize the sun vector uncertainty. The method is applied here to find the optimal configuration for a single photodiode and a trio of photodiodes by mapping the design parameters (photodiode mounting angles) to the resulting measurement uncertainties over every direction in the body-fixed frame, and those directions are subsequently used to form an objective function.

Beyond photodiodes, the method is generally applicable to directional sensors and instruments. For example, it could be used to determine a body-fixed solar panel configuration to maximize power generation, or to find antenna orientations.

References


Summary

We have developed calibration techniques that significantly improve the accuracy of low-cost attitude sensors used on small satellites. The sensor calibrations are performed on-orbit and do not require attitude knowledge. Since rigorous pre-flight calibration and high tolerance assembly are no longer required, this significantly decreases the development time and costs of satellites. We have also developed a method to optimize the orientation of directional sensors in the spacecraft body frame. This is used in the design phase of the spacecraft to maximize the performance of directional sensors or instruments, such as photodiodes, solar panels, or antennae.

These methods result in significant improvements in the accuracy of low-cost sensors that are commonly used on small spacecraft, enabling more capable spacecraft. Future work includes extending these methods to enable completely new architectures, such as sensors that reconfigure themselves on-orbit to track optimal configurations.