Celestial Blue

Verification of IMU Strapdown and Kalman Filter

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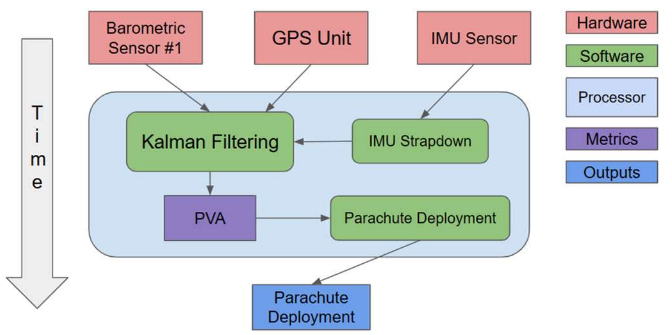
Introduction

For this tech note, I'll explain the systems engineering diagram of our flight computer, discuss our software algorithms, explain our verification process, and discuss our results at the time of writing this document.

Software System

The software for our flight computer can best be visualized as the following:



Our software system takes input from:

- <u>One barometric sensor</u>, which provides altitude by measuring air pressure
- <u>One GPS unit</u>, which provides latitude, longitude, and altitude
- <u>One IMU sensor</u>, which provides acceleration and angular rotation

Our software system runs the following data processing algorithms:

- <u>IMU Strapdown,</u> to convert IMU data to position, velocity, and attitude (PVA).
- <u>Kalman Filtering,</u> which uses the strapdown output to achieve a more optimal PVA.

Our system produces the following output:

- <u>Parachute deployment</u>

Verifying our software system

Before launching our computer on a real rocket, we verified that our software was implemented correctly using *test data*. This test data allows us to run our software and simulate the flight path of a rocket.

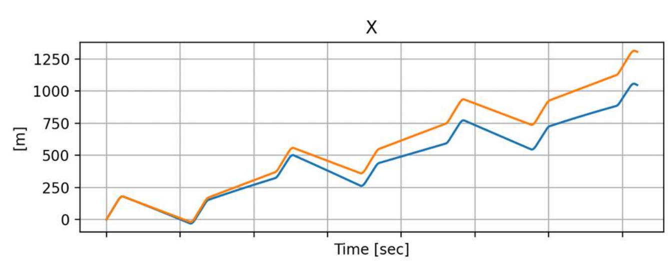
We generated some sensor data as inputs to our software, and generated the corresponding PVA data to compare with the outputs of our software.

For example, we can pass the generated acceleration and rotation data into our IMU strapdown and compare its output with the generated PVA data. We can run a similar scenario for our Kalman filter.

Below, we describe our two software algorithms: how they work, and what our results look like.

IMU Strapdown

The IMU strapdown is an algorithm that takes the IMU acceleration and rotation, and converts them to PVA. We have verified that the strapdown output is correct by comparing it (blue) to our test data (orange):



An unfortunate side effect of the IMU strapdown, even when implemented correctly, is that there is a bit of drift between the test data position and IMU strapdown. This is expected. We fix this by using Kalman filtering, which is described on the next page.

Kalman Filtering

The Kalman Filtering algorithm is used to reduce the error in the IMU strapdown to get a more accurate measurement of PVA.

Mathematics of Kalman Filtering

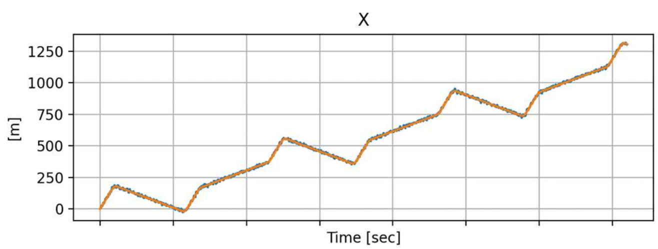
If you have two sensors with standard deviation σ_1 and σ_2, then Kalman filtering can let you combine the results in such a way that the new standard deviation is less than both σ_1 and σ_2.

The first step of Kalman filtering is to define a state vector x. The state vector contains all the data you care about predicting. For instance, our state vector contains PVA. With lots of complex math, the state vector gets updated at every given time step and represents the best estimate of our PVA.

Kalman Filter for GPS / IMU Error Reduction

Recall that the IMU strapdown computes PVA. The estimate can be improved by Kalman filtering with the GPS, which is what we do in our software.

We have verified that the Kalman output is correct by comparing it (blue) to our test data (orange):



As you can see, there is much less of a drift between the expected output and the achieved output; in fact, the outputs are so close that the orange line appears to be stacked on top of the fuzzy blue line.

With this system in place, our flight computer is well on the way to accurately predicting PVA for parachute deployment.

Conclusion

The pairing of the IMU strapdown with the Kalman filter is what allows our flight computer to have the most accurate PVA calculation at any given moment. At the time of writing this document (4/13/2023), we've verified that the software works with our test data, and we are now in the process of testing this software with the actual hardware sensors.

The next steps for us would be:

1. To include a barometer in the Kalman filtering to further improve PVA estimates.
2. To complete the parachute deployment logic.
3. To test the device on an actual rocket.

As an above-and-beyond, we would hope to add a data transmission functionality. This would allow a hobbyist to be able to see the rocket's PVA displayed on their own computer in real time, meaning the user could evaluate the flight of their rocket as it's happening.

References *(Annotated)*

1. J. Zhang, E. Edwan, J. Zhou, W. Chai and O. Loffeld, "Performance investigation of barometer aided GPS/MEMS-IMU integration," *Proceedings of the 2012 IEEE/ION Position, Location and Navigation Symposium*, 2012, pp. 598-604, doi: 10.1109/PLANS.2012.6236933.

This paper explains that you can use Kalman filtering to fuse GPS with IMU. Their experimentation indicates that PVA results are more accurate when doing so.

2. Steffes, Stephen. Development and analysis of SHEFEX-2 hybrid navigation system experiment. Diss. Bremen, Universität Bremen, Diss., 2013, 2013.

This paper is rather dense but includes the 9x9 state propagation matrix for our Kalman filtering of PVA. It was sent to us by our sponsors Ian and Tyler.

3. T. Klein, I. Fletcher; "Intro to Kalman Filters," Presentation. 9 Nov 2022

Our sponsors Ian and Tyler gave us this presentation on Kalman filtering and the IMU Strapdown; their presentation slides were super helpful for our understanding of these topics. The slides were easy to digest and included just the right amount of information needed.