Kalman Filter for SunSat

Why and How?

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1 Introduction

The SunSat avionics includes a dedicated subsystem for parachute deployment and attitude determination activities. Each of these two distinct tasks require some sort of state estimation based on the inputs from sensors during flight. This iteration of the Nova platform is using a passive parachute deployment system, but future iterations may use an active system. Active deployment should be triggered at the point of apogee in the flight to minimise loading and chances of damage, and for this to happen, sensor data needs to be processed appropriately such that the point of apogee can be detected to a sufficient degree of accuracy in real-time.

To estimate the states of a system, we would ideally use a huge suite of sensors to log every possible output over the period of interest. However, this is obviously a very complex, expensive, and sometimes impossible task. Instead, we want to be able to measure certain states of the vehicle by processing the data from existing, low-cost sensors. For example, we want to know the velocity of the satellite. We want to know velocity because we can then use the point of $u_z = 0$ to be the point of apogee (the vertical (z-axis) velocity is zero at the maximum height). However, we don't really have any practical means of directly measuring this.

- We can't use a rotary speed sensor - as used in cars - as we don't have any rotational motion that we can measure and translate into linear velocity
- We can't use a pitot tube - as used by aircraft - as we are enclosed in the rocket's payload section and so wind speed is not measurable.

We can, however, use an accelerometer. Acceleration is the first time derivative of velocity, and therefore, velocity is the integral of acceleration over the interval $[0, t]$.

$$a = \frac{du}{dt} \tag{1.1}$$

$$u = \int_0^t a \mathrm{d}t \tag{1.2}$$

And so if we want to measure the velocity of our satellite, surely we can just integrate the output from out accelerometer in the z-direction? That would be great if we were living in an ideal world, but sadly our measurements are quite far from ideal... We're just taking snapshots of the measurement at discrete time intervals. This means that when we integrate, we're missing out on a bunch of readings. In these readings there will be actual acceleration variation as well as a bunch of noise - such is life. So long story short, it's not quite as simple as just integrating our acceleration.

Additionally, it would be nice to have access to 'smoothed' or 'accurate' acceleration data. We know that the vehicle acceleration isn't actually varying as the output from our sensor tells us it is - the noise is giving us a false impression of what the vehicle is actually doing.

A Kalman Filter will (hopefully) help us solve these problems! ... but what is a Kalman Filter? I'll try to explain this without getting too far into the nitty gritty of the control theory.

2 What is a Kalman Filter?

Lets say we had a **perfect** model of our system. We modelled every single particle of fuel in the rocket motor, accounted for the gravitational pull of Jupiter, and even managed to mathematically describe the current status of the entire atmosphere, allowing us to predict in which direction the wind would be blowing in a few months time. Using all of this information, we should be able to know the states (acceleration, velocity, position, etc.) of our vehicle at some arbitrary time without even having to use any sensors! But back in the real world, this is completely ridiculous, of course.

Instead, we typically model our systems in some simplified way. Maybe we just consider our vehicle as a point mass, or neglect the change in air density as altitude increases, for example. This way, we can sensibly approximate our system, and we can use this simplified model to our advantage. By itself, this would allow us to at least make a guess about the acceleration of our vehicle at an arbitrary point in time. But remember, we have sensors to help us out! We can compare the acceleration as measured by the accelerometer to our guess based on the simplified model to refine our estimate and hopefully bring it as close to reality as possible. That's handy! It would also be helpful if we could account for the fact that we're not just going to be flying straight up - uncertainties in the environment (e.g. wind) are going to be pushing us around in some 'random' way that we aren't able to predict.

And **that** is what a Kalman Filter does for us! It is a way of using imperfect sensor data in a system full of uncertainties, along with a simplified model of the dynamics, in order to estimate the *actual* states of the system.

3 Why should we use one?

Kalman Filters do a pretty great job of estimating the system states. They are able to account for dynamic changes in the system that might have completely slipped your mind during the planning phase. Obviously there are limitations, and for sure this iteration will not be perfect, but that's why we test and develop these things! Especially now that the apogee detection and attitude determination subsystems are not mission-critical, it is the perfect time to test new things out.

The Kalman Filter will allow us to process the data from our sensors and turn it into something much more useful at a low cost. We won't need a fancy sensor suite, and hopefully it can tell us which sensors we can do without in future versions, to further reduce the cost and weight of the vehicle. It's also very computationally lightweight. It doesn't require much memory as you only need to keep hold of information about the current and previous states, and the calculations at each time step are not overly complex (though this depends on the model to an extent...).

With all of this in mind, the Kalman Filter is a perfect candidate for getting as much useful data as we can. It's a method that is well suited for high-speed embedded systems, and one that is used frequently in space systems (even in the Apollo guidance computers!).

4 Kalman Filter as a part of the parachute deployment activities