Solutions to Integration Drift of a Gyroscope

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Introduction:

Inertial Measurement Units (IMU’s) are devices commonly used in the technology industry for calculating a devices orientation. A devices orientation is typically given by its rotation around its three axes. Roll is the rotation around a body’s X axis, Pitch is its rotation around its Y axis, and Yaw is its rotation around its Z axis. A standard 6 degrees of freedom IMU typically consists of a three-axis gyroscope and a three-axis accelerometer. The gyroscope measures a body’s angular velocity and the accelerometer measures the forces acting upon it. With some calculations, a body’s orientation given by its angles off a coordinate plan can be calculated. A body’s Pitch and Roll can be calculated using both accelerometer data and with gyroscope data, while a body’s Yaw can only be calculated using Gyroscope data. By taking the integral of the angular velocity over time around an axis, its absolute orientation can be calculated. However, there is inherent risk with this method as gyroscope data tends to be faulty over time due to integration drift. Gyroscopes have built in bias instability, which is the error in its initial zero reading. If a gyroscope does not have a perfect zero reading, this error will accumulate over the time of the integration and lead to larger deviation between calculated orientation and actual orientation. There are methods to minimize this error. Among the most popular methods is filtering. There are two common filters used to help integration drift, Kalman and Complementary. In addition to filtering, many IMU’s include magnetometers to help calculate yaw. Perhaps the most obvious method to mitigate against error due to drift is to use gyroscope with low bias instability.

Figure 1: Graphic of Roll, Pitch, Yaw

Filtering:

Kalman Filter

One of the most widely use filters for orientation estimation is a Kalman filter. At a high level, a Kalman filter is feedback system that estimates a state using uncertain measurements and the systems previous state. Kalman filters work best with system that are linear or near linear and when the noise or uncertainty in the system is gaussian. A Kalman filter is most useful when there is uncertainty in the measurements of state. This occurs when the sensors used are noisy, prone to interference, or in the case of gyroscope, susceptible to compounding error. The Kalman filter produces an estimation of the current state by computing a weighted average of the systems predicted state and the measurements of the systems current state. A weighted average is used since the uncertainty of the measurement and the prediction typically not equal. The weights used in a Kalman filter are derived from the covariance of the system. This filter is iterative and repeated with ever time step. The linear estimation of the system is created using the last optimal state estimation. While Kalman filters are useful and accurate, they are known to be complicated, difficult to use, and increase the systems run time complexity.

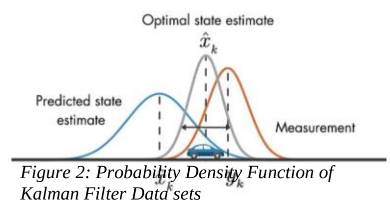

Figure 2: Probability Density Function of Kalman Filter Data sets

Complementary Filter

A second type of filtering used commonly for IMU orientation is a complementary filter. A complementary filter combines the data from the accelerometer and the gyroscope to estimate a body's Pitch and Roll. Roll and pitch can be calculated from accelerometer data using the following equations:

$$Roll = tan^{-1}(\frac{Ay}{Az})$$

$$Pitch = tan^{-1}(-Ax/(\sqrt{Ay^2 - Az^2}))$$

With Ax, Ay, and Az being the acceleration in the X, Y, and Z axes respectively. A complementary filter takes the angle from accelerometer, passes it through a lowpass filter and adds it with the high-passed signal from the integral of the gyroscope data. The purpose of the low-pass filter is to eliminate any of the fluctuations of the accelerometer due to vibrations, and the high-pass filter is to limit the gyroscope integration drift by cutting the DC offset. An important feature of the complementary filter is that the frequency response at any frequency of the LPF and the HPF sum to one. The time constant of the filters dictates how much the angle calculation relies on the gyroscope data verses the accelerometer data. The positives of a complementary filter are that they are easy to implement and do not require nearly as much runtime as Kalman filters. The draw back of a complementary filter is that they are not applicable for calculating Yaw and are less accurate than Kalman filters.

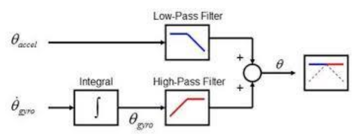

Figure 3: Complementary Filter

IMU Features:

Magnetometers:

Many IMU's on the market today include three-axes magnetometers which can also be used to calculate orientation. A magnetometer measures the strength of a magnetic field and can be used to find a body' alignment with the Earth's magnetic field. Yaw can be calculated using the following formula:

$$Yaw = \text{atan}\,(\frac{My}{Mx})$$

With My and Mx being the strength of the magnetic field in Y and X axes, respectively. This calculation can be used in tandem with the gyroscope data to help eliminate integration drift. The fault with magnetometers is that the magnetic field is susceptible to anomalies on the order of the Earth's magnetic field, corrupting the Yaw calculation.

High Quality Gyroscope

The most intuitive way to eliminate integration drift is to use a gyroscope with a small bias instability. The quality of gyroscope and IMU range with price and manufacturing quality. There are two main type of gyroscopes used in industry today, Fiber Optic Gyros (FOGs) and Micro-Electro-Mechanical Systems (MEMS) Gyros. FOGs use optical beams and the Sagnac effect to measure rotation. They typically are moderately priced and used in tactical and industry grade applications. MEMs use Coriolis Effect on a vibrating mass to measure rotation. These gyroscopes are typically cheaper, smaller, and used in applications from consumer grade to industrial. A cheaper MPU6050 IMU will use a MEMS gyroscope and will have a larger instability bias than a state of the art IMU. While the ADIS1690 Six Degree of Freedom IMU uses a higher-grade MEMS gyroscope and has a Bias Instability of 1.8°/hr. The range of gyroscope precision typically correlates directly with cost. A more accurate gyroscope will cost more money.

Conclusion

There are a variety of solutions for the problem integration drift poses to calculating a body's orientation. Each solution has trades off in the domain of run time complexity and or cost. Finding the correct solutions boils down to the computing and monetary constraints of a project in addition to the experience of the Engineer. While a developing Kalman might be a more robust, controllable solution, it will require significantly more work than using a complementary filter with a higher quality IMU with a small bias instability. Regardless, the diversity of solutions means there is most likely going to be a method that is optimal for providing protections orientation error.

References

[1] "A Buyer's Guide to IMU Sport Sensor Devices for Professionals." https://simplifaster.com/articles/buyers-guide-imu-sensor-devices/ (accessed Nov. 15, 2019).

[2] P. Patonis, P. Patias, I. N. Tziavos, D. Rossikopoulos, and K. G. Margaritis, "A Fusion Method for Combining Low-Cost IMU/Magnetometer Outputs for Use in Applications on Mobile Devices," *Sensors (Basel)*, vol. 18, no. 8, Aug. 2018, doi: 10.3390/s18082616.

[3] "Beginner's Guide to IMU | Robotics Club." http://students.iitk.ac.in/roboclub/2017/12/21/Beginners-Guide-to-IMU.html (accessed Nov. 12, 2019).

[4] M. Marron *et al.*, "Comparing a Kalman Filter and a Particle Filter in a Multiple Objects Tracking Application," in *2007 IEEE International Symposium on Intelligent Signal Processing*, Alcala de Henares, Spain, 2007, pp. 1–6, doi: 10.1109/WISP.2007.4447520.

[5] "Complementary filter - My IMU estimation experience." https://sites.google.com/site/myimuestimationexperience/filters/complementary-filter (accessed Dec. 21, 2019).

[6] "Complementary filter and Kalman filter introduction," *Issuu*. https://issuu.com/onghenggneesayshi/docs/complementary_filter_and_kalman_filter (accessed Dec. 22, 2019).

[7] "Inertial measurement unit," *Wikipedia*. Oct. 10, 2019, Accessed: Nov. 12, 2019. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Inertial_measurement_unit&oldid=920526717.

[8] "Selecting an Inertial Measurement Unit (IMU) for UAV Applications | Unmanned Systems Technology." https://www.unmannedsystemstechnology.com/2018/11/selecting-an-inertial-measurement-unit-imu-for-uav-applications/ (accessed Nov. 15, 2019).

[9] "The Case of the Misguided Gyro | Analog Devices." https://www.analog.com/en/analog-dialogue/raqs/raq-issue-139.html# (accessed Dec. 20, 2019).

[10] "Understanding Kalman Filters, Part 1: Why Use Kalman Filters? Video - MATLAB." https://www.mathworks.com/videos/understanding-kalman-filters-part-1-why-use-kalman-filters--1485813028675.html (accessed Nov. 12, 2019).

[11] "WP_Guide_to_Comparing_Gyros_IMUs_web.pdf." Accessed: Dec. 22, 2019. [Online]. Available: https://kpp-public.s3.amazonaws.com/WP_Guide_to_Comparing_Gyros_IMUs_web.