UAV Attitude Estimation

Alex Mejlevang Ellegaard - aelle20@student.sdu.dk
Anders Lind-Thomsen - andli20@student.sdu.dk
Peter Skibdal Frydensberg - pefry20@student.sdu.dk
Thomas Therkelsen - ththe20@student.sdu.dk

September 18th 2024

3 UAV attitude exercises

3.1 UAV attitude sensors

A Micro Electro-Mechanical System (MEMS) accelerometer measures the drone's acceleration along one axis. Inside the accelerometer is a small object coupled to some springs. When the drone accelerates, the small object moves correspondingly, and some fixed capacitive plates detect its movement.

A MEMS gyro is used to measure the angular velocity of the drone along one axis. A small object within the gyro is set to vibrate back and forth with some fixed velocity. When the gyro is exposed to an angular velocity, the Coriolis force makes the gyro move at an angle perpendicular to the velocity of the motion, which is then detected by some fixed capacitive plates.

To calculate the compass course, the drone needs to know its orientation with regards to roll and pitch given by the gyros and accelerometers, since the magnetometer can't determine the drone's course when the pitch is for example 90 degrees since the magnetic field lines would lay perpendicular to the drone.[1]

3.2 UAV attitude sensing using accelerometers

3.2.1 Calculate pitch angle

The pitch angle of a YXZ-coordinate frame is the rotation around the X-axis and is given as

$$\phi_{yxz} = \tan^{-1}\left(\frac{G_y}{\sqrt{G_x^2 + G_z^2}}\right). \tag{1}$$

Using (1) on the data in *imu_razor_data_pitch_55deg.txt* gives the result shown on figure 1. Here it is clearly seen that the drone rotates 55°forwards and back as expected.

3.2.2 Calculate roll angle

The roll angle of a YXZ-coordinate frame is the rotation around the Y-axis and is given as

$$\phi_{yxz} = -\frac{G_x}{G_z} \tag{2}$$

Using (2) on the data from *imu_razor_data_roll_65deg.txt* gives the result shown on figure 2. Here it is clearly seen that the drone rolls 65 °to each side as expected.

3.2.3 Accelerometer noise

Roll and pitch were measured when the IMU was lying still on a table, which resulted in the graph shown of figure 3 where it is seen that both roll and pitch have a lot of noise upwards of ±1.5°. The noise could be mitigated by using a low-pass filter or a better sensor.

[1] How To Mechatronics, "How MEMS Accelerometer Gyroscope Magnetometer Work & Arduino Tutorial", Published on Nov 19th 2015, Accessed on Sep 17th 2024, `https://www.cnmoc.usff.navy.mil/Our-Commands/United-States-Naval-Observatory/Precise-Time-Department/Global-Positioning-System/Global-Positioning-System-Overview/`

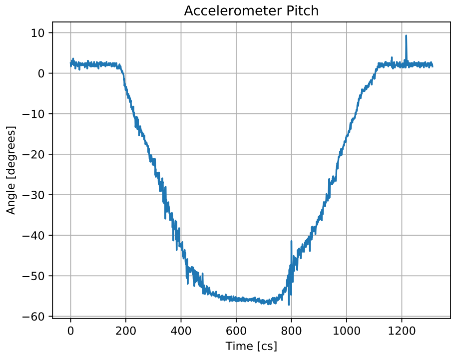

Figure 1: Pitch calculated from accelerometer data

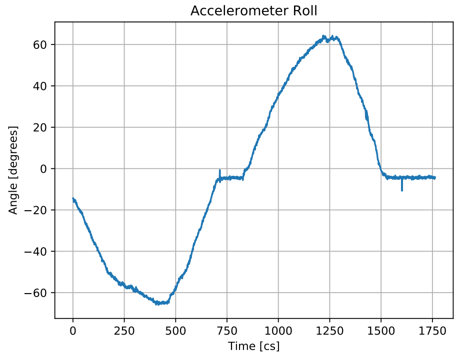

Figure 2: Roll calculated from accelerometer data

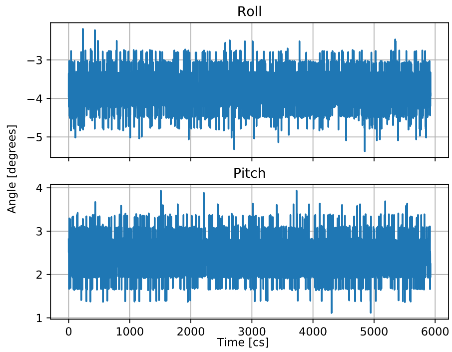

Figure 3: Static accelerometer noise

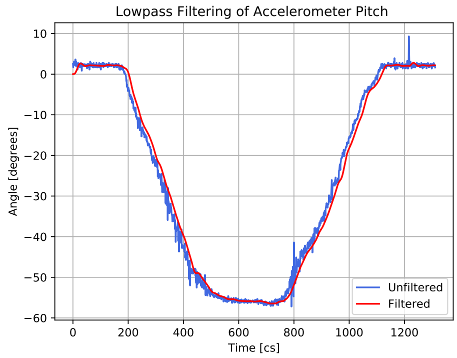

Figure 4: Filtered accelerometer pitch

3.2.4 Low-pass filtering

To reduce the noise of the accelerometer signal, fourth-order Butterworth low-pass filter has been used with the cutoff frequency $f_c = 3$Hz. The filtered signal is shown together with the unfiltered signal in figure 4. Here it can be seen that the filter is adding a delay of approximately couple of hundred milliseconds. This value is not acceptable if you have high speed controller.

3.2.5 Limitations of Euler angles

Gimbal lock is the phenomenon that happens when two axes of rotation align in parallel thus removing one degree of freedom. This causes the system to be able to only rotate along two axes of rotation instead of three. This can, for example, occur if an object gets rotated 90 degrees around the Y axis (in an XYZ frame). Gimbal lock can be mitigated so that all possible states of orientation can be described by using a oientation representation with a higher number of independent variables than three. This could be rotation matrices (9 values) or quaternions (4 values). [2]

3.3 Gyro measurements

3.3.1 Calculating relative angle

The relative angle around the Z-axis is found by performing numerical integration of the angular velocity. Doing this on the data from *imu_razor_data_yaw_90deg.txt* gives us the graph shown in figure 5.

[2] Adrian Popa, "Re: What is meant by the term gimbal lock?", Published on June 4th 1998, Accessed on Sep 17th 2024, `https://www.madsci.org/posts/archives/aug98/896993617.Eg.r.html`.

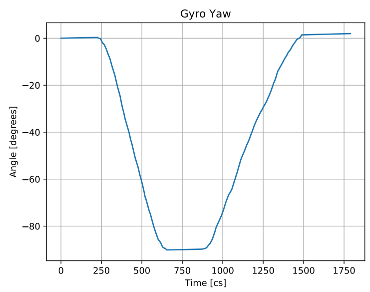

Figure 5: Integrated angular velocity

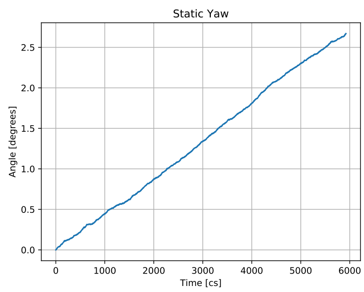

Figure 6: Integrated static angular velocity

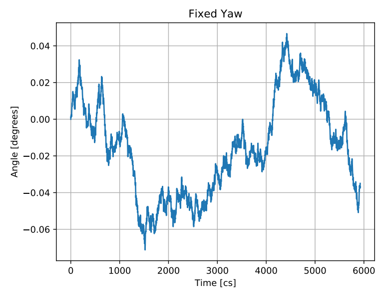

Figure 7: Integrated static angular velocity, without bias

3.3.2 Static data & 3.3.3 Observing bias

Similarly, integrating the static data gives the graph shown on figure 6, which shows a noticable bias in the angle drift. The error accumulates over time because of the numerical integration. By calculating the mean of the static dataset, it can then be subtracted from the dataset. The result from this is shown on figure 7.

3.3.4 Bias sources

Mechanincal errors when producing the gyro with regards to friction or numerical errors in rounding when reading from the device.

3.4 Kalman filter

3.4.1 Implementing a scalar Kalman filter

To obtain an optimal estimate of the pitch, a Kalman filter has been implemented with the gyro as the precise but relative measurement combined with the accelerometer as the noisy but absolute measurement. The signal from the kalman filter can be seen on figure 8.

```
# Kalman prediction step (we have new data in each iteration)
    estAngle += gyro_x * dt
    gyroVarAcc += gyroVar
    estVar += gyroVarAcc * dt
# Kalman correction step (we have new data in each iteration)
    k = estVar / (estVar + pitchVar)
    estAngle = estAngle + k * (pitch - estAngle)
    estVar = estVar * (1 - k)
    gyroVarAcc = 0
```

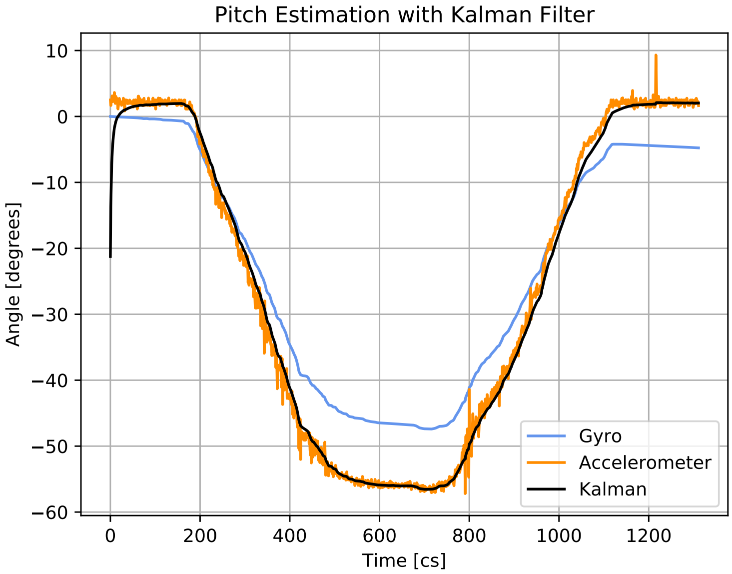

Figure 8: Kalman filter