

Sensors

Note: This section is currently under revision.

Sensors produce measurements that reflect the state of the external world - plus some noise. This section will go through what various sensors are measuring, their sources of noise, and how to relate them to states we want to keep track of.

Towards the end, a large example Emission Matrix will be given that demonstrates how to integrate several sensors into a Kalman Filter.

Accelerometer

An Accelerator measures acceleration. It's traducer is tantamount to a heavy mass in a box, connected to each wall by a spring. As the box gets accelerated from a direction, the mass's inertia resists, so the spring on one side is compressed, and the spring on the other is expanded. By measuring this contraction/expansion, the acceleration is estimated.

Modern microchip accelerometers are thin pieces of silicon, produced with similar fabrication techniques as microprocessors. The motion of the silicon chip is measured by changing the distance in several capacitors, which measurably alters the capacitance. However, the simpler mass-spring conceptualization is easier to talk about, so we'll stick with that.

The accelerometer feels all forces. This include gravity. If you push on a box, the mass will [relatively speaking] move in the opposite direction of acceleration. However, if you place the box on a table, gravity will cause it to sag, compressing the bottom spring and extending the top spring. The accelerometer will interpret it as being pushed *upwards*, not downwards. As such, we can see that *body* forces, like gravity, are not actually felt by the accelerometer. Only normal forces generated in response to them.

All together, an accelerometer feels 4 different forces. Gravity, Centripetal Acceleration, Rotational Acceleration, and Translational Acceleration.

$$A = a_t + a_r + a_c + a_g$$

Gravity

The accelerometer feels all forces. This include gravity. If you push on a box, the mass will [relatively speaking] move in the opposite direction of acceleration. However, if you place the box on a table, gravity will cause it to sag, compressing the bottom spring and extending the top spring. The accelerometer will interpret it as being pushed *upwards*, not downwards. As such, we can see that *body* forces, like gravity, are not actually felt by the accelerometer. Only normal forces generated in response to them.

We can safely assume that gravity is always pulling *downwards*, by definition. However, it will not

always add a static acceleration vector along the positive z-axis, because our sensor does not stay level. In fact, measuring gravity gives you an indication of an external static vector. The measurement of this vector is affected by your orientation. Conversely, by measuring your relation to this vector, you can help determine your orientation.

It should be noted that, due to the other sources of acceleration, utilizing an accelerometer's measurements to define your z-axis is likely to be very noisy.

So sitting still at orientation $R(\psi, \phi, \theta) = R(0, 0, 0)$ the accelerometer would measure $[0, 0, +g]$ for $g \approx 9.8 \frac{m}{s^2}$. If pitched upwards at 45° , the gravity vector would be detected by the positive z and positive x axis at 45° . This transformation would be tantamount to a *negative* pitch forward by the gravity acceleration relative to the accelerometer. As such, the *Inverse* Rotation Matrix $R^{-1} = R'$ describes how the gravity vector is rotated due to the submarine's orientation.

$$a_g = R^T \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} = \begin{bmatrix} 0 & 0 & g \end{bmatrix} R$$

Centripetal Acceleration

The centripetal acceleration felt by the accelerometer is give by the equation $\frac{v^2}{r} = \omega r^2 = \dot{\theta}^2 r$. In 3 dimensions, we need to consider how this force is felt from rotation about each axis.

We can consider an accelerometer aligned with the submarine's internal x, y, z axis located at Position $[p_x, p_y, p_z] = p[1, 1, 0]$. A rotation of $\dot{\theta} = 0.5 \frac{rad}{sec}$ about the z-axis (yaw) would constitute a rotational velocity. The radius $r = \sqrt{x^2 + y^2} = \sqrt{2}$. So the centripetal force $a_{c:yaw} = (0.5^2)(\sqrt{2}) = \frac{1}{4}\sqrt{2} = \sqrt{\frac{2}{2}} = 1 \frac{m}{s^2}$.

We can also find that the z-position p_z of the submarine would not impact the centripetal acceleration felt by the accelerometer. This calculated value would hold for any $p[1, 1, p_z]$.

However, how will this force be detected by the accelerometer? Centripetal Acceleration is another body force. It is accelerating all masses towards the outside - the accelerometer then feels the *inward* normal force created by the rigid structure it's attached to preventing it from moving in the face of the acceleration. So the acceleration vector measured will be negative, pointing back at the origin.

Furthermore, the acceleration felt will be broken up across sensors. Some proportion of it will be felt as negative acceleration along the x-axis, and some proportion along the y-axis. Consider instead if the accelerometer was at the position $p[\sqrt{2}, 0, 0]$. The centripetal acceleration felt would be the same, but it would be measured entirely as a positive x component $a_{c:yaw} = [-\sqrt{2}, 0, 0]$.

Were it at position $p[0, \sqrt{2}, 0]$ the entirety of the acceleration would be felt as a y component $a_{c:yaw} = [0, -\sqrt{2}, 0]$.

We can generalize the solution and calculate the centripetal force felt from roll, pitch, and yaw rotational velocity from an arbitrary $p[x, y, z]$ position.

The position does not influence the rotational velocity - all rotations are felt equally regardless of position on rigid bodies. This leaves the radius to be calculated. The radius $r = \sqrt{p_x^2 +$

p_y^2} \$. The angle of this force acts on the accelerometer is also the angle formed from the center of rotation (origin) $\theta = \tan\{\frac{p_y}{p_x}\}$ \$.

The math works out quite conveniently.

$$r = \sqrt{p_x^2 + p_y^2}, \quad \theta = \arctan\{\frac{p_y}{p_x}\} \quad p_x = r\cos\{\theta\}, \quad p_y = r\sin\{\theta\} \\ a_x = \omega^2 r\cos\{\theta\}, \quad a_y = \omega^2 r\sin\{\theta\}$$

Therefore:

$$a_x = \omega^2 p_y, \quad a_y = \omega^2 p_x, \quad a_z = 0$$

The trigonometric terms cancel out and the acceleration detected along each axis is proportional to the position along that axis. Therefore, we've calculated the a_c contribution from yaw. We can generalize this calculation to roll and pitch.

Yaw

$$r = \sqrt{p_x^2 + p_y^2}, \quad \theta = \arctan\{\frac{p_y}{p_x}\} \quad p_x = r\cos\{\theta\}, \quad p_y = r\sin\{\theta\} \\ a_x = -\omega^2 r\cos\{\theta\}, \quad a_y = -\omega^2 r\sin\{\theta\} \quad a_x = -p_x * \omega^2, \quad a_y = -p_y * \omega^2, \quad a_z = 0$$

Pitch

$$r = \sqrt{p_x^2 + p_z^2}, \quad \theta = \arctan\{\frac{p_z}{p_x}\} \quad p_x = r\cos\{\theta\}, \quad p_z = r\sin\{\theta\} \\ a_x = \omega^2 r\cos\{\theta\}, \quad a_z = \omega^2 r\sin\{\theta\} \quad a_x = p_x * \omega^2, \quad a_y = 0, \quad a_z = p_z * \omega^2$$

Roll

$$r = \sqrt{p_y^2 + p_z^2}, \quad \theta = \arctan\{\frac{p_z}{p_y}\} \quad p_y = r\cos\{\theta\}, \quad p_z = r\sin\{\theta\} \\ a_y = \omega^2 r\cos\{\theta\}, \quad a_z = \omega^2 r\sin\{\theta\} \quad a_x = 0, \quad a_y = p_y * \omega^2, \quad a_z = p_z * \omega^2$$

Total Summation

Putting this all together we get the total centripetal acceleration felt on an accelerometer at position $[p_x, p_y, p_z]$ with rotational velocities $\dot{R} = [\dot{\psi}, \dot{\phi}, \dot{\theta}]$.

$$a_x = (0 * \dot{\psi}^2) + (-p_x * \dot{\phi}^2) + (-p_x * \dot{\theta}^2) \quad a_y = (-p_y * \dot{\psi}^2) + (0 * \dot{\phi}^2) + (-p_y * \dot{\theta}^2) \\ a_z = (-p_z * \dot{\psi}^2) + (-p_z * \dot{\phi}^2) + (0 * \dot{\theta}^2)$$

Thus we can turn this into a matrix format and get:

$$a_c = \begin{bmatrix} a_{cx} \\ a_{cy} \\ a_{cz} \end{bmatrix} = \begin{bmatrix} 0 & -p_x & -p_x \\ -p_x & -p_y & 0 \\ -p_y & -p_z & -p_z \end{bmatrix} \begin{bmatrix} \dot{\psi}^2 \\ \dot{\phi}^2 \\ \dot{\theta}^2 \end{bmatrix}$$

$\dot{\theta}^2$

Finally, it's worth noting that because the accelerations felt are a function of rotational velocity squared, the direction of rotation is irrelevant. The force felt is inwards, and favors neither direction. We know this about centripetal force intuitively, but it's nice to see math reflected our common-sense.

Translational and Rotational Acceleration

The Translational and Rotational Accelerations are both felt as individual point-accelerations. Rotational Acceleration only makes sense as the difference of accelerations felt on two parts of a rigid body. The translational acceleration of the body is the average of these accelerations.

Assume two accelerometers are placed at locations $p_1[1,0,0]$ and $p_2[-1,0,0]$. An acceleration of $1\frac{m}{s^2}$ along the x-axis would be measured as $a_1[1,0,0]$ and $a_2[1,0,0]$. They would be felt equally. A yaw acceleration $\alpha_{yaw} = \frac{a}{r} = 1\frac{rad}{sec^2}$ about the origin would be felt as a sideways acceleration on each accelerometer. The forward accelerometer would be accelerated to the left, into the positive y-axis. The back accelerometer would be accelerated in the opposite direction, into the negative y-axis. Thus the accelerations felt would be $a_1[0,1,0]$ and $a_2[0,-1,0]$. They would experience opposite accelerations.

$$a_t = \frac{a_1 + a_2}{2}, \quad a_r = \frac{a_1 - a_2}{2}$$

It should also be noted, that this math describes the translational acceleration felt by the center of rotation. That is defined as the origin, or center of mass, for convenience. But it can technically be defined as any arbitrary set of coordinates. Demonstrating that is an exercise left to the student.

However, this only works for two accelerometers placed along a common axis at equal distances. We want generalized equations for arbitrary accelerometer placement.

Consider if the two accelerometers were instead placed at $p_1[0,1,0]$ and $p_2[0,-1,0]$ and subjected to the same translational acceleration $a_t=[1,0,0]$. The translational accelerations felt would be equal to the first case. Translational acceleration is felt universally on the rigid body. Subjected to the same rotational acceleration of $\alpha_{yaw} = 1\frac{rad}{sec^2}$, however, the left accelerometer would be accelerated backwards toward the negative x-axis, with $a_1[-1,0,0]$ and the right accelerometer would feel an opposite acceleration forward $a_2[1,0,0]$. Were the acceleration doubled to $\ddot{\theta} = 2\frac{rad}{sec^2}$, the accelerations felt would be equal to $[-2,0,0]$ and $[2,0,0]$.

Like in the centripetal acceleration case, the z-axis position does not affect the rotational forces felt by a yaw acceleration. Using trigonometry, we can find the calculations for acceleration components felt from a given yaw acceleration at an arbitrary point. Again, like with the centripetal force, the rotational force components will depend will depend on angle $\theta = \tan^{-1}\left(\frac{p_y}{p_x}\right)$. The difference is the acceleration felt will be orthogonal to that vector, rather than lie alongside it.

$$p = [p_x, p_y, p_z], \quad \alpha = \frac{a}{r} \quad r = \sqrt{p_x^2 + p_y^2}, \quad \theta = \arctan\left(\frac{p_y}{p_x}\right) \\ p_x = r\cos{\theta}, \quad p_y = r\sin{\theta} \quad a_x = -\alpha * r\sin{\theta}, \quad a_y = \alpha * r\cos{\theta} \quad a_x = -p_y * \alpha, \quad a_y = p_x * \alpha, \quad a_z = 0$$

Note that the acceleration vector is felt orthogonal to the position of the accelerometer. Thus, the

rotational acceleration vector felt from a yaw acceleration is equal to the position vector $[p_x, p_y, p_z]$ crossed with the z-axis $[0, 0, 1]$, scaled by the actual yaw acceleration about the z-axis. This is why we get the p_x term for the y component, but a negative p_y term for the x component, and a 0 along the z-axis.

We can take this method of finding the acceleration vector and apply it to pitch and roll accelerations, to find the total rotational acceleration felt.

Yaw

$$p = [p_x, p_y, p_z], \quad \alpha = \frac{a}{r} \quad \parallel \quad r = \sqrt{p_x^2 + p_y^2}, \quad \theta = \arctan\left(\frac{p_y}{p_x}\right) \quad \parallel \quad p_x = r \cos\{\theta\}, \quad p_y = r \sin\{\theta\} \quad \parallel \quad a_x = -\alpha * r \sin\{\theta\}, \quad a_y = -\alpha * r \cos\{\theta\} \quad \parallel \quad a_x = -p_y * \alpha, \quad a_y = p_x * \alpha, \quad a_z = 0$$

Pitch

$$p = [p_x, p_y, p_z], \quad \alpha = \frac{a}{r} \quad \parallel \quad r = \sqrt{p_x^2 + p_z^2}, \quad \theta = \arctan\left(\frac{p_z}{p_x}\right) \quad \parallel \quad p_x = r \cos\{\theta\}, \quad p_z = r \sin\{\theta\} \quad \parallel \quad a_x = \alpha * r \sin\{\theta\}, \quad a_z = -\alpha * r \cos\{\theta\} \quad \parallel \quad a_x = p_z * \alpha, \quad a_y = 0, \quad a_z = -p_x * \alpha$$

Roll

$$p = [p_x, p_y, p_z], \quad \alpha = \frac{a}{r} \quad \parallel \quad r = \sqrt{p_y^2 + p_z^2}, \quad \theta = \arctan\left(\frac{p_z}{p_y}\right) \quad \parallel \quad p_y = r \cos\{\theta\}, \quad p_z = r \sin\{\theta\} \quad \parallel \quad a_y = -\alpha * r \sin\{\theta\}, \quad a_z = \alpha * r \cos\{\theta\} \quad \parallel \quad a_y = -p_z * \alpha, \quad a_z = p_y * \alpha$$

Total Summation

Putting this all together we get the total acceleration felt on an accelerometer at position $[p_x, p_y, p_z]$ with rotational acceleration $\dot{R} = [\ddot{\psi}, \ddot{\phi}, \ddot{\theta}]$.

$$a_x = (0 * \dot{\psi}^2) + (p_z * \dot{\phi}^2) + (-p_y * \dot{\theta}^2) \quad \parallel \quad a_y = (-p_z * \dot{\psi}^2) + (0 * \dot{\phi}^2) + (p_x * \dot{\theta}^2) \quad \parallel \quad a_z = (p_y * \dot{\psi}^2) + (-p_x * \dot{\phi}^2) + (0 * \dot{\theta}^2)$$

Whatever value remains after the rotational components have been removed is the true translational acceleration a_t . Thus we can turn this into a matrix format and get:

$$a = a_t + a_r = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & p_z & -p_y \\ 0 & 1 & 0 & -p_z & 0 & p_x \\ 0 & 0 & 1 & p_y & -p_x & 0 \end{bmatrix} \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \\ \ddot{\psi} \\ \ddot{\phi} \\ \ddot{\theta} \end{bmatrix}$$

us out of any information. It may also be worth investigating accelerometers placed precisely at the origin, and unit vectors along each axis, to see if there's any theoretical information available, but realistic constraints prevent us from every placing accelerometers so precisely.

Thus, there are only 9 of those values that can be determined from accelerometers alone. To find which states are linked, we can systematically remove columns from the matrix and re-test its rank. If the rank diminishes, then that column was an independent vector and corresponds to a state not ineffably tied to the value of any other state.



By removing up to two columns at a time, we can find any pair of columns that are mutually dependent. The first and third collection of three columns are both clearly independent, as removing any one of them diminishes the rank by 1, and removing any 2 diminishes the rank by 2. They correspond to the rotational and centripetal accelerations. That leaves the rotation matrix elements, and the translational accelerations as co-dependent.

This makes sense, as an object can not tell the difference between [normal forces opposing] gravity and acceleration. Rotational and centripetal accelerations can be sensed out because they are felt differently based on position. Translational acceleration and gravity are felt equally and universally.

Anyway, as this shows, we need some other information from another sensor to fix the values of either the translational accelerations, or the pitch and roll of the system, in order for us to estimate the other state variables. It also shows that we need only 3 3-axis accelerometers to collect all unique data. Anything beyond this will just provide redundant information that reduces noise - helpful, but not vital. The Kalman filter allows us to make estimations of all states absent other measurements, since it uses the forward-predicted values of the states as additional pseudo-measurements, which in and of itself is a full-rank 'measurement'. However, those measurements will not be very accurate. Accelerometers should be augmented with more sensors.

Gyroscopes

Gyroscopes are nice and simple. They measure the rotational velocity about an axis. 3 together provide you with a direct measurement of your roll, pitch, and yaw velocities $\dot{\psi}, \dot{\phi}, \dot{\theta}$. Rotational velocity is felt equally in all placed on a rigid body, so placement of the gyroscopes does not factor in (though proper alignment with the x, y, z axes of the submarine's intrinsic coordinate system is necessary).

Gyroscopes are, however, subject to drift. As they operate, the velocity will have some offset. As a function of temperature and time, this offset value will slowly change. Over short instances it is not problematic - the estimates of angular acceleration $\ddot{\psi}, \ddot{\phi}, \ddot{\theta}$ the Kalman Filter will generate based off gyroscope measurements will be very accurate. However, the rotational velocity itself is an important measurement and should be accounted for.

$$G = \begin{bmatrix} G_{\dot{\psi}} \\ G_{\dot{\phi}} \\ G_{\dot{\theta}} \end{bmatrix} = \begin{bmatrix} \dot{\psi} \\ \dot{\phi} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} \text{err}_{\dot{\psi}} \\ \text{err}_{\dot{\phi}} \\ \text{err}_{\dot{\theta}} \end{bmatrix}$$

This presents a problem. We have two unknown values - the true velocity measurement, and the offset, for every one piece of information - the Gyroscope measurement.

Thus the system must be calibrated. On Start-up, we need to externally fix the rotational speed of the submarine to $[\dot{\psi}, \dot{\phi}, \dot{\theta}] = [0, 0, 0]$ and then take a measurement of what remains. That will be the offset values.

This is generally sufficient. However, submarine missions will run for long periods of time. Competition runs take up to 20 minutes, and pool tests see the submarine in the water for potentially hours at a time.

Error Tracking

A possible solution is to have the system itself track the offset of each axis of each gyroscope as an extra state variable. Mathematically, the set-up would look like this:

$$\begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\psi} \\ \dot{\phi} \\ \dot{\theta} \\ \text{err}_{\dot{\psi}} \\ \text{err}_{\dot{\phi}} \\ \text{err}_{\dot{\theta}} \end{bmatrix} = \begin{bmatrix} G_{\dot{\psi}} \\ G_{\dot{\phi}} \\ G_{\dot{\theta}} \end{bmatrix}$$

Obviously, this will have trouble working on its own. We have 6 unknown values and only 3 measurements. However, let's see what happens when we use an additional gyroscope.

$$\begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{\psi} \\ \dot{\phi} \\ \dot{\theta} \\ \text{err}_{\dot{\psi}} \\ \text{err}_{\dot{\phi}} \\ \text{err}_{\dot{\theta}} \\ \text{err}_{2\dot{\psi}} \\ \text{err}_{2\dot{\phi}} \\ \text{err}_{2\dot{\theta}} \end{bmatrix} = \begin{bmatrix} G_{1\dot{\psi}} \\ G_{1\dot{\phi}} \\ G_{1\dot{\theta}} \\ G_{2\dot{\psi}} \\ G_{2\dot{\phi}} \\ G_{2\dot{\theta}} \end{bmatrix}$$

This is better. Now we have 9 unknowns and 6 measurements. However, no matter how many gyroscopes we add, we will always be 3 measurements short. We need some prime gyroscope with no error to definitively fix the rotational rates, after which the remaining gyroscopes could be used to solve for their own errors.

This doesn't really seem to help us at all. We wouldn't need to track offset errors if we could make a perfect gyroscope. Alone, gyroscopes cannot track their own error.

However, we're not alone. We've got other sensors, and a Kalman Filter. The Kalman Filter provides predicted locations as state variable measurements based on previous states. And the Kalman Filter's states are informed by multiple sensors, including absolute orientation information obtained from magnetometers, accelerometers, and depth sensors, among other things.

Thus, through the Kalman Filter, the sensors describing orientation will also estimate the derivative of orientation - the rotational velocity. If a magnetometer continues to point in the same direction while a gyroscope *insists* the submarine is yawing at $5^\circ/\text{sec}$, the Kalman Filter will resolve the two, estimate a velocity of $2.5^\circ/\text{sec}$ and an orientation to match. The gyroscope's drift will be estimated to be $+2.5^\circ/\text{sec}$. On the next measurement 1 second later, the magnetometer will indicate a heading of -2.5° and suggest a yaw velocity of $-2.5^\circ/\text{sec}$ while the gyroscope, will assert a rotational velocity of $2.5^\circ/\text{sec}$, after subtracting its offset. The Kalman Filter will again resolve this, and estimate a gyroscopic drift closer to $5^\circ/\text{sec}$, after which the gyroscope and magnetometer should continue to be in agreement until significant drift accumulates in the gyroscope again.

In reality, it is not quite as clean as the above example. In that example, the derivative measurement of the magnetometer was assumed to be absolutely correct, and the gyroscope did not resist its drift changing by several degrees in a few seconds. Gyroscopes do not drift that quickly, and the offset should know and assert that. Meanwhile, magnetometers will also be noisy, and jump around within a certain range, so their noise will inform the system not to trust it - or derivatives derived from its changes between time-steps, to be fully trusted. The Kalman Filter properly informed will still slowly adjust the drift until the gyroscope and magnetometer converge at some point, but it will do so according to the weight given to the two sensors and the offset based off of noise.

As part of the Process noise, the gyroscope's offsets must be given their own value which indicates it's likelihood to drift over time. This value will come into conflict with the error measured between the noisy gyroscope and magnetometer. Too high of a process noise, and all disagreements between the two sensors will just be attributed to a rapidly changing offset error, and the actual gyroscope measurements will not contribute to the state estimation. Too low of a Process Noise, and the gyroscope will stubbornly believe itself over the magnetometer (or other orientation sensors) and force the Filter to estimate significantly deflected headings as rotational. Finding a proper balance between the weights given to the magnetometer, gyroscope, and offset drift noise is the key to resolving this issue.

If it can be resolved, however, you will have a gyroscopic system that does not need calibration on start-up, nor suffer from drift during long operation. It should be stated however, that calibration is always good to perform when possible. Introducing a temporary 'calibration sensor' that asserts rotational velocity to be 0 with ~ 0 variance will force the gyroscopes to set their offsets to the current value no matter what.

Magnetometer

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