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Intelligent Precision Sensing

3 IMU Sensor Fusion Troublemakers and How You Can Outsmart Them

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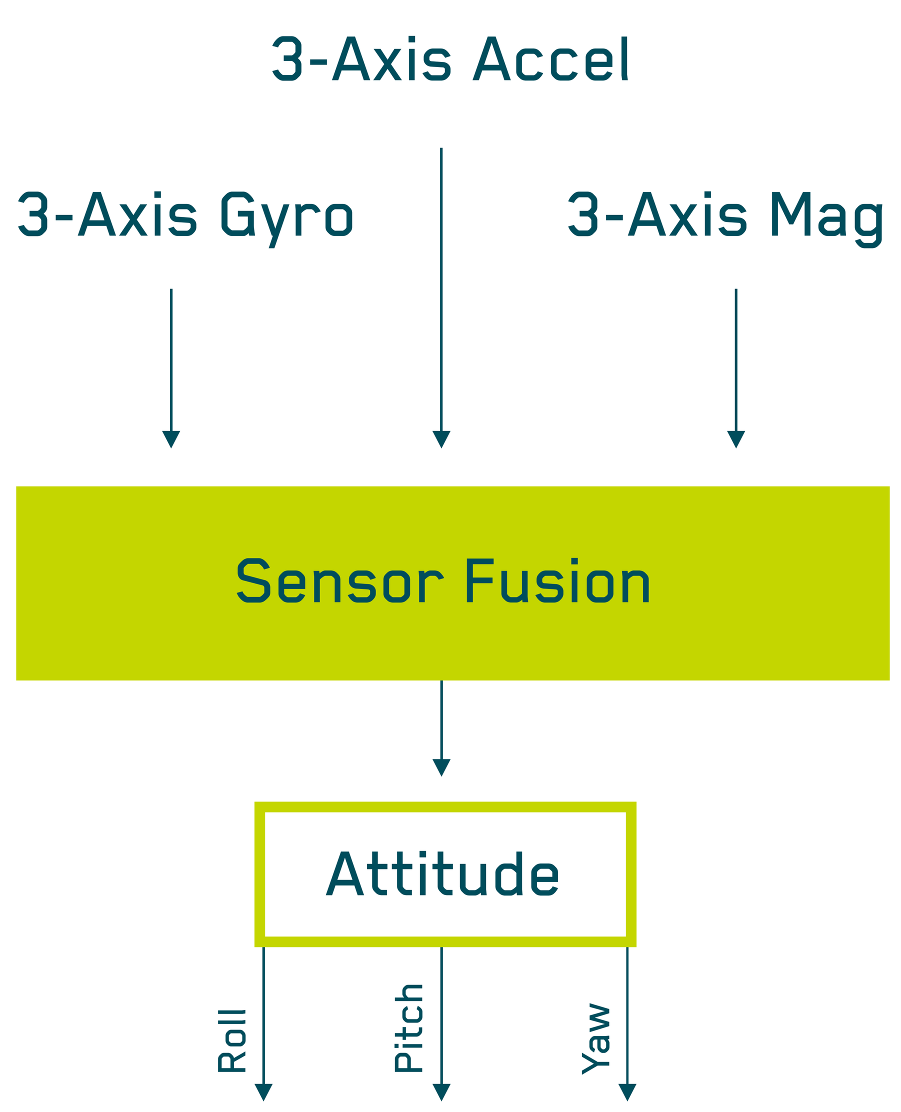
Whitepaper

IMU sensor fusion algorithms estimate orientation by combining data from the three inertial sensors. The goal of these algorithms is to reconstruct the roll, pitch and yaw rotation angles of the device in its reference system.
Fusing data of different sensors helps to compensate for these three main troublemakers:

- Gyroscope drift
- Magnetic perturbation
- External acceleration

Here you can see an example of sensor fusion software that uses dedicated algorithms to handle these troublemakers.



Introduction

Sensor fusion is the intelligent combination of data from different sensors to achieve a particular goal. Sometimes, a single sensor output might even be insufficient to handle the task.

For example, if the goal is to estimate the position for a navigation system, the use of GPS signal alone is insufficient if the satellite signal is lost (e.g., in a tunnel). It is therefore necessary to fuse GPS information with other sensors that help the system to operate reliably in all conditions.

An Inertial Measurement Unit (IMU) system typically includes several inertial sensors: a 3D accelerometer, a 3D gyroscope and a 3D magnetometer. IMU sensor fusion algorithms estimate orientation by combining data from the three sensors. The goal of these algorithms is to reconstruct the roll, pitch and yaw rotation angles of the device in its reference system.

IMU Sensor Fusion algorithms are based on an orientation estimation filter, such as the Kalman filter and the constant coefficient filter. They typically include three algorithmic steps:

- Prediction
- Observation
- Update

In the first step, the state estimated from the previous timestep is used to predict the current state. It focuses on the mathematical integration of angular velocity (gyroscope output), whereas the magnetometer and accelerometer are unnecessary for this step.

In the second step, depending on static or dynamic conditions, accelerometer and magnetometer data complete the estimation of the tilting and heading of the device. The accelerometer provides the distribution of the gravity components along its axes, while the magnetometer contributes the distribution of the earth's magnetic field along the axes. Finally, there's the update step. It balances the output of prediction and observation to ensure the most accurate results.

Fusing data from different sensors helps to compensate for these three main troublemakers:

1. Gyroscope drift
2. Magnetic perturbation
3. External acceleration

Let's have a look at each of these problems and their solutions.

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1. Gyroscope Drift

The first step in compensating for gyroscope offset is to calibrate it. Unfortunately, as external and working conditions can change over time, calibration is not always enough to compensate for gyroscope drift. For this reason, it is essential to include data from the accelerometer and magnetometer as well.

Accelerometers, gyroscopes and magnetometers can be affected by structural errors due to external and working conditions. These errors cause misalignment of the sensors' intra-axes and the device's body axes and a bias in the signal, which is a constant offset along the three axes.

Orientation estimation based on gyroscope data is obtained by the integral calculation of its 3-axis components. Therefore, removing the drift is crucial. In fact, the integration of an offset leads to a drift of the orientation estimation even in static conditions.

The first step in compensating for the offset is to calibrate the gyroscope. Unfortunately, as external and working conditions can change over time, calibration is not always enough to compensate for gyroscope drift. For this reason, it is essential to include data from the accelerometer and magnetometer as well.

1.1. Calibration - Before Sensor Fusion

The first thing to do when solving gyroscope drift is to calibrate the system. This process aims to remove gyroscope bias and inter-axes misalignment with the device.
Removing the bias is the simplest step. It is enough to let the device remain static, measure data for a sufficient time, and then remove the mean value of the signal in the section, which corresponds to the bias.

The hardest part is to find the matrix that describes the scale factors between the sensor axes to compensate for inter-axes misalignment.
While the accelerometer and magnetometer have measurable natural fields (gravitational field and earth's magnetic field), the gyroscope doesn't have one. Therefore, you'll need to create it artificially using specific instruments.

You typically execute the calibration procedure before running the sensor fusion algorithm. But you can also perform bias estimation and removal in real-time as part of the sensor fusion algorithm.

1.2. Use Accelerometer Data

The calibrated accelerometer is part of the sensor fusion algorithm and operates in the observation step. It helps to compensate for gyroscope drift both in static and dynamic conditions.
Accelerometer data helps to correct the tilting estimation (roll and pitch information) of a gyroscope by providing the gravity constant of your system. The acceleration tilting outputs run in real-time and are more reliable in static conditions, as explained later.

1.3. Use Magnetometer Data

A calibrated magnetometer helps to estimate the heading orientation of the device during the algorithm observation step. It provides data based on the physics of the earth's magnetic field component. Unfortunately, magnetometers are difficult to manage because of magnetic perturbations.

To calibrate the magnetometer, you extract the scale factors and the offset of the system.
Fortunately, the earth's magnetic field is constant across a large percentage of the earth's surface.
Therefore, you can obtain the data for the calibration parameters by simply rotating the system along the three axes.

2. Magnetic Perturbations

The world around us is full of electronic devices and ferromagnetic materials. These objects can interfere with the magnetometer detection of the earth's magnetic field. Some of these interferences are soft-iron perturbations, while others are hard-iron perturbations. The magnetometer is quite sensitive to these perturbations, and the following considerations can improve the reliability of its output:

2.1. Calibration - Before Sensor Fusion

Like the gyroscope, you'll need to calibrate the magnetometer. To do so, you extract the scale factors and the offset of the system. Fortunately, the magnetic field is constant across a large portion of the earth's surface. Therefore, you can obtain the data for the calibration parameters by simply rotating the system along the three axes.

2.2. Magnetometer Runtime Signal

There are different strategies for handling magnetic perturbations in an orientation estimation filter:

- Avoid using the magnetometer if you're unsure how to recognize and manage perturbed magnetic data. The heading component is still handled by the gyroscope integration. Consequently, a drift phenomenon might occur for that angle.
- Ignore the magnetometer only when necessary: you can recognize the perturbation in real-time and ignore magnetic data only for the duration of the disturbance.
  In this solution, the algorithm uses gyroscope integration for the heading component only when necessary.

3. External Acceleration

The presence of motion, which means external acceleration, makes it harder to recognize the gravity components along the axes. This difficulty can be a source of errors in the tilting estimation derived from accelerometer data. It can also contaminate the estimation of the heading coming from gyroscope and magnetometer data. The methods below can help to overcome these errors.

3.1. Calibration - Before Sensor Fusion

As with the gyroscope and magnetometer, you'll have to calibrate the accelerometer to compensate for structural errors. The calibration procedure is easy to implement.
It consists of positioning the device at different angles with respect to gravity and taking mean values of the static at each position. From the measured acceleration values, you can calculate the accelerometer scale factors as well as the offset.

3.1. Accelerometer Runtime Signal

In static conditions, the accelerometer reads mainly gravity acceleration, which you can easily translate into tilting information.
In dynamic conditions, however, it is more challenging to extrapolate the gravity component from the external acceleration components. To do so, you have to low-pass filter the accelerometer data with a low cut-off frequency. You can then filter the gravity component that is ever constant in your system from the signal.

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Summary

Sensor fusion is the intelligent combination of data from different sensors to achieve a particular goal. In this context, IMU sensor fusion algorithms estimate orientation by combining data from the accelerometer, gyroscope and magnetometer in three steps: Prediction, Observation, and Update. The fusion of data from different sensors helps compensate for the three main troublemakers: Gyroscope drift, magnetic Perturbation and External Acceleration.

Here you can see an example of sensor fusion software that uses dedicated algorithms to handle all three troublemakers.

To solve these problems, you need to calibrate the IMU sensors first, as they suffer from internal structural errors. Further, accelerometer and magnetometer data can help to correct gyroscope tilting and heading estimation. Then, magnetic disturbances can be handled at runtime by avoiding the use of the magnetometer or compensating for magnetic perturbations. Finally, accelerometer data must be low-pass filtered to extract tilting information even under dynamic conditions.

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